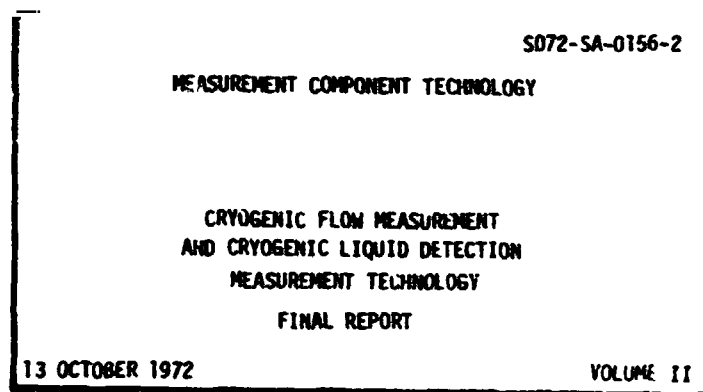


F13933

(NASA-CR-120227) MEASUREMENT COMPONENT  
TECHNOLOGY. VOLUME 2: CRYOGENIC FLOW  
MEASUREMENT AND CRYOGENIC LIQUID DETECTION  
MEASUREMENT TECHNOLOGY (North American  
Rockwell Corp.) 93 p HC \$7.75 CSCL 20L

N74-27186

Unclas  
G3/23 40513



Contract NAS7-200

*K. K. Hayakawa*  
K. K. Hayakawa  
Task Manager  
Launch Vehicles Engineering



 Space Division  
North American Rockwell

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR.





#### FOREWORD

This report documents the work performed by North American Rockwell Corporation through its Space Division in fulfillment of a Task Authorization entitled, "Measurement Component Technology," sponsored by the National Aeronautics and Space Administration's George C. Marshall Space Flight Center, Huntsville, Alabama, under contract NAS7-200 in accordance with Task Authorization 2026-TA-36. The work was performed by members of the Electrical and Electronics Systems branch of the Space Systems and Applications Division during the period July 12, 1971 through October 13, 1972. NASA technical monitors were Messrs. W. T. Escue, S&E-ASTR-IM, H. S. Herman and R. C. Holder, S&E-ASTR-IMP, J. P. Hamlet, S&E-ASTR-IMF and J. E. Zimmerman, S&E-ASTR-INT.

The report consists of three volumes, of which this is Volume II. Volume numbers, document numbers and volume titles are listed below.

- Volume I - Cryogenic Pressure Measurement Technology and Subjects Allied to Pressure Transducers. Document Number SD72-SA-0156-1.
- Volume II - Liquid Detection Measurement Technology and Cryogenic Flow Measurement Technology. Document Number SD72-SA-0156-2.
- Volume III - Cryogenic Temperature Measurement Technology and High Temperature Strain Gage Technology. Document Number SD72-SA-0156-3.

PRECEDING PAGE BLANK NOT FILMED

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR.



#### ACKNOWLEDGEMENTS

The authors are indebted to the many companies and Government Agencies listed below who have contributed information and assistance during the preparation of this report. Also, acknowledgements are made to the many authors whose publications, which are referenced in the bibliography, have been used as reference sources for information contained in this report.

Acoustica Associates  
Automation Industries, Inc.  
Avion, Inc., Instrumentation Division  
Bell & Howell/Consolidated Electrodynamics  
Bendix Corporation  
BLH Electronics, Inc.  
Bourns, Inc.  
Comarc, Avionics Sales Division  
Consolidated Controls  
Cox Instrumentation  
Delaware Manufacturing Co.  
Dentronics, Inc.  
Dynamics Corporation  
Eastech, Incorporated  
Electro Development Corporation  
Fisher and Porter  
Flow Technology, Incorporated  
Foxboro Instruments  
General Electric Company  
Genisco Technology Corporation  
Hastings-Raydist  
Honeywell, Incorporated  
Hy-Cal Engineering  
Industrial Nucleonics Corp.  
ITT Barton  
Kistler Instrument Corporation  
Liquid Meter Corporation  
MB Electronics  
Microdot, Inc., Instrumentation Division  
Micro-Measurements  
National Bureau of Standards (Boulder, Colorado)  
Product Specialist - Metal V-Seal Parker Seal Co.  
Quantum Dynamics, Incorporated  
RdP Corporation  
Revere Corporation  
Rosemount Engineering  
Servo Mechanism  
Simmonds Precision Products, Inc.  
Stetham Instruments, Inc.  
Thermo-Systems, Incorporated  
Trans-Sonics, Inc.  
Tyco Laboratories  
United Controls  
Victory Engineering  
Vinson Manufacturing Company  
Wyle Laboratories



#### ACKNOWLEDGEMENTS

The work performed in this study was accomplished by a team under the direction of Study Manager K. K. Hayakawa. R. M. Chrisco performed the investigation into hydrogen embrittlement of pressure transducer materials. C. S. Greenough conducted the research into high pressure flange sealing. M. M. Iwata investigated bridge designs for platinum wire thermometry. C. F. Lytle investigated cryogenic liquid detection and temperature transducers. D. R. Udell conducted the study into cryogenic flowmeters, close-coupled versus remotely installed pressure transducers and temperature compensation designs for strain gage pressure transducers. J. A. Walling performed the investigation into high temperature strain gages.

# TECHNICAL REPORT INDEX/ABSTRACT

ACCESSION NUMBER		DOCUMENT SECURITY CLASSIFICATION	
		UNCLASSIFIED	
TYPE OF DOCUMENT			LIBRARY USE ONLY
CRYOGENIC FLOW MEASUREMENT AND CRYOGENIC LIQUID DETECTION MEASUREMENT TECHNOLOGY			
AUTHOR(S)			
HAYAKAWA, K.K., UDELL, D.R., IWATA, M.M., LYTLE, C.F., CHRISO, R.M., GREENOUGH, C.S., WALLING, J.A.			
CODE	ORIGINATING AGENCY AND OTHER SOURCES		DOCUMENT NUMBER
ON 085282	SPACE DIVISION, NORTH AMERICAN ROCKWELL CORPORATION DONNEY, CALIFORNIA		SD72-SA-0156-2
PUBLICATION DATE		CONTRACT NUMBER	
OCTOBER 13, 1972		NAS7-200	
DESCRIPTIVE TERMS			
TRANSDUCERS		LIQUID DETECTION TRANSDUCERS	
FLOWMETERS			
PRESSURE TRANSDUCERS			
STRAIN GAGES			
FLANGE SEALS			
HYDROGEN EMBRITTLEMENT			
TEMPERATURE TRANSDUCERS			
ABSTRACT			
<p>THIS REPORT DOCUMENTS THE RESULTS OF AN INVESTIGATION INTO THE AVAILABILITY AND PERFORMANCE CAPABILITY OF MEASUREMENT COMPONENTS IN THE AREA OF CRYOGENIC TEMPERATURE, PRESSURE, FLOW AND LIQUID DETECTION COMPONENTS AND HIGH TEMPERATURE STRAIN GAGES. IN ADDITION, TECHNICAL SUBJECTS ALLIED TO THE COMPONENTS WERE RESEARCHED AND DISCUSSED. THESE SELECTED AREAS OF INVESTIGATION WERE: (1) HIGH PRESSURE FLANGE SEALS, (2) HYDROGEN EMBRITTLEMENT OF PRESSURE TRANSDUCER DIAPHRAGMS, (3) THE EFFECTS OF CLOSE-COUPLED VERSUS REMOTE TRANSDUCER INSTALLATION ON PRESSURE MEASUREMENT, (4) TEMPERATURE TRANSDUCER CONFIGURATION EFFECTS ON MEASUREMENTS, AND (5) TECHNIQUES IN TEMPERATURE COMPENSATION OF STRAIN GAGE PRESSURE TRANSDUCERS.</p> <p>THE PURPOSE OF THE PROGRAM WAS TO INVESTIGATE THE LATEST DESIGN AND APPLICATION TECHNIQUES IN MEASUREMENT COMPONENT TECHNOLOGY AND TO DOCUMENT THIS INFORMATION ALONG WITH RECOMMENDATIONS FOR UPGRADING MEASUREMENT COMPONENT DESIGNS FOR FUTURE S-II DERIVATIVE APPLICATIONS. RECOMMENDATIONS ARE PROVIDED FOR UPGRADING EXISTING STATE-OF-THE-ART IN COMPONENT DESIGN, WHERE REQUIRED, TO SATISFY PERFORMANCE REQUIREMENTS OF S-II DERIVATIVE VEHICLES.</p>			

FORM 1511-4 REV 1 68

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR.

# CONTENTS

	Page
1.0 INTRODUCTION . . . . .	1
2.0 SUMMARY . . . . .	5
3.0 CRYOGENIC FLOW MEAS. TECHNOLOGY . . . . .	14
3.1 Technical Discussion . . . . .	15
3.2 Flow Measurement Design Considerations . . . . .	18
3.3 Survey Results of Available Designs . . . . .	19
3.4 Densitometer Candidates . . . . .	59
3.5 Application of an Available Design . . . . .	60
4.0 CRYOGENIC LIQUID LEVEL DETECTION MEASUREMENT TECHNOLOGY . . . . .	69
4.1 Technical Discussion . . . . .	69
4.2 Evaluation of Available Designs . . . . .	70
4.3 Survey Results of Currently Available Systems . . . . .	71
4.4 Tabulation of Liquid Detection Systems . . . . .	80
BIBLIOGRAPHY . . . . .	82

# ILLUSTRATIONS

Figure		Page
3.3.1-1	The Bondix Inferential Mass System . . . . .	22
3.3.3-1	The Eastech Bluff Body Schematic . . . . .	25
3.3.4-1	Mass Momentum Meter Assembly . . . . .	27
3.3.4-2	Flow Meter Installation . . . . .	28
3.3.4-3	Mass Meter Cutaway . . . . .	29
3.3.5-1	The Fisher and Porter Turbine Meter . . . . .	32
3.3.6-1	The Flow Technology Turbine Meter . . . . .	33
3.3.7-1	The Foxboro Mass Momentum Meter . . . . .	34
3.3.7-2	The Foxboro Mass Meter Installation . . . . .	35
3.3.8-1	The General Electric Mass Flow Meter . . . . .	36
3.3.8-2	Cutaway View of the Mass Meter . . . . .	38
3.3.9-1	Mass Flow Meter Schematic and Flow Relationship . . . . .	40
3.3.10-1	Mass Meter Schematic . . . . .	41
3.3.10-2	Mass Meter System Diagram . . . . .	42
3.3.11-1	ITT Barton Densitometer . . . . .	45
3.3.11-2	ITT Barton Densitometer Detector Schematic . . . . .	46
3.3.12-1	Quantum Dynamics Turbine Meter Cutaway . . . . .	48
3.3.12-2	Quantum Dynamics Inferential Mass System . . . . .	49
3.3.13-1	Ramapo Drag Body Volumetric Meter . . . . .	50
3.3.14-1	Rosemount Thermal Mass Flowmeter Diagram . . . . .	52
3.3.15-1	Simmonds Precision Inferential Mass Flow System . . . . .	54
3.3.15-2	Simmonds Precision Flow Mass System Schematic . . . . .	55
3.3.16-1	Thermo-Systems Thermal Mass Meter Schematic . . . . .	57
3.3.16-2	Thermo-Systems Mass Meter Installation Cutaway . . . . .	58
4.3.1-1	Acoustica Ultrasonic Sensor System . . . . .	71
4.3.3-1	Acoustica Infrasonic Sensor System . . . . .	73
4.3.4-1	Bendix Cryogenic Optical Sensor . . . . .	74
4.3.5-1	Bendix Radio Frequency Sensor System . . . . .	75
4.3.8-1	Simmonds Precision Coaxial Capacitance System . . . . .	77
4.3.8-2	Simmonds Precision Point Sensor Ring System . . . . .	78



#### TABLES

	Page
3.6-1 Flowmeter Manufacture Survey Table . . . . .	64
3.6-2 Candidate Design Comparison Table . . . . .	67
3.6-3 Acceptable Flowmeter Table . . . . .	68
4.4-1 Liquid Detection System Design and Performance Features .	81



#### DEFINITION OF TERMS AND ABBREVIATIONS

Cryogenic - Any temperature less than -100 F.

Reynolds No. - A dimensionless ratio of inertia forces divided by viscous forces.

Pickoff - A sensor or transducer.

Transition Point - That point at which a change of state takes place over a short temperature span.

Bond Number - The relationship between a media's surface tension and the gravitational environment it sees.

Linear Momentum - The product of the body mass ( $\dot{M}$ ) and the body linear velocity ( $V$ ).

Angular Momentum or Moment of Momentum - The product of mass ( $\dot{M}$ ), the tangential component of velocity ( $V_u$ ), and the radius to the point of exit ( $R$ ).

## 1.0 INTRODUCTION

As space missions become more complex and more demanding, the requirements on measurements grow more and more difficult. Constant improvements in measurement techniques and accuracy are being sought by design engineers for a more accurate evaluation of system performances. Ever increasing severity in operating environments requires a continued search for new designs and techniques.

Greater reliability of equipment is required as space missions grow more complex. Lower component weight, smaller size and lower electrical power consumption are sought as mission duration grows longer. All of these factors and many more require that measurement capabilities be upgraded to meet these new demands. The purpose of this study is to satisfy some aspects of this need with an investigation into measurement component technology.

S-II derivative systems, including the Space Tug, Orbiting Propellant Depot (OPD), Expendable Second Stage (ESS), and Chemical Interorbital Shuttle (CIS) impose many new performance requirements on measurement components not currently required by the S-II stage or the Saturn V vehicle.

Higher measurement accuracy, long term operation in high and low temperature environments, repeated operations in relatively high vibration environments, long term shelf life and repeated reuses are some of the more important performance requirements. Light weight, small package size, simplified wiring requirements, low electrical power, and simplified maintenance procedures are other desirable characteristics for future space vehicles.

This program investigated the availability and performance capability of specific measurement components in the area of cryogenic temperature, pressure, flow and liquid detection components and high temperature strain gages. The study conducted a systematic survey of manufacturers to establish performance and physical characteristics of current designs. In cases where current state-of-the-art equipment cannot meet performance requirements for future space missions, the design shortcomings are identified and recommendations for improvements, where available, were presented and discussed. The study evaluated published information and supplier furnished data and discussed some advantages and disadvantages for given designs. Measurement system application design considerations were investigated and discussed in the report where these considerations were an important part of the measurement. The results of the investigation were intended to provide a useful reference source for design and component information for the selection and application of the measurement transducers of this investigation.

In addition, specific technical topics allied to the measurement type or components were researched and are discussed in this report. Items selected for investigation as part of this study were selected for the problem nature of the item or for the technical value of the researched information as a reference source for new designs. Selected areas for investigation were (1) high pressure flange seals, and (2) hydrogen embrittlement of pressure



transducer materials. Other topics which involve application were (1) the effects of close-coupled versus remote transducer installation on pressure measurements, (2) temperature transducer configuration effects on measurements, and (3) techniques in temperature compensation of close-coupled strain gage pressure transducers.

These specific measurement component capabilities and technical topics are contained in three volumes. Volume I contains Cryogenic Pressure Measurement Technology, High Pressure Flange Seals, Hydrogen Embrittlement of Pressure Transducer Materials, the Effect of Close-Coupled Versus Remote Transducer Installations on Pressure Measurements, and Techniques in Temperature Compensation of Strain Gage Pressure Transducers. Volume II consists of Cryogenic Flow Measurement Technology and Cryogenic Liquid Detection Measurement Technology. Volume III summarizes Cryogenic Temperature Measurement Technology and High Temperature Strain Gage Technology.

#### CRYOGENIC PRESSURE MEASUREMENT TECHNOLOGY

The investigation into cryogenic pressure transducer technology was made by conducting a survey of manufacturers to establish transducer capability of currently available equipment. The requirement established for the search was to locate an instrument capable of operating with liquid oxygen or liquid hydrogen systems of a space vehicle while maintaining temperature sensitivity errors within 2 percent of full scale.

Since the investigation did not result in meeting this design goal, a literature research was conducted to identify problem areas which contribute to this transducer performance limitation.

This report presents the results of the industrial survey and the literature research.

#### HIGH PRESSURE FLANGE SEALS

Consideration of a high pressure (5000 psi) transducer for applications whose design concept utilized flanged mounting precipitated this investigation. The research work primarily addresses itself to the search for a metallic seal to attain optimum sealing for low temperature, high pressure systems. The investigation relied principally upon published literature as the source for information.

#### HYDROGEN EMBRITTLEMENT OF PRESSURE TRANSDUCER MATERIALS

The hydrogen embrittlement investigation utilized published literature for obtaining information on the susceptibility of transducer materials to the embrittlement problem. The investigation emphasized the practical approach by categorizing transducer metals with respect to embrittlement susceptibility. The investigation did not deal with the atomic structure or metallurgical aspects of metals.



#### THE EFFECTS OF CLOSE-COUPLED VERSUS REMOTE TRANSDUCER INSTALLATION ON PRESSURE MEASUREMENTS

A technical discussion on the effects of close-coupled versus remote transducer installation effects on measurement accuracy was presented in this report for reference information to transducer users. The discussion in the report was based on information derived from Saturn S-II flight tests and laboratory work performed in conjunction with investigations into the Saturn S-II low frequency oscillation phenomenon. Data distortion due to line length is illustrated and corrective methods are delineated.

#### TECHNIQUES IN TEMPERATURE COMPENSATION OF STRAIN GAGE PRESSURE TRANSDUCERS

Another topic presented in the report is based on investigations of temperature sensitivity problems of strain gage pressure transducers. Since the Saturn S-II low frequency oscillation phenomenon resulted in utilizing close-coupled strain gage transducers on the LOX feedlines of engine 1 and 5, an investigation was made to establish techniques available for compensation of temperature sensitivity errors. This information is provided in this report as reference material.

#### CRYOGENIC MASS FLOW MEASUREMENT TECHNOLOGY

The flow investigation researched current technology for systems capable of cryogenic temperature flow measurements. Manufacturers were contacted for information on their product line of flowmeters which indicated promise of meeting an application requiring a mass gas flowmeter.

A hypothetical case for a cryogenic temperature gas flow measurement was established for the purpose of assessing whether any of the candidate systems would be acceptable for this case. The report provides the technical discussions resulting from this evaluation as well as descriptions of individual manufacturers systems.

#### CRYOGENIC LIQUID DETECTION MEASUREMENT TECHNOLOGY

The cryogenic liquid detection technology portion of this study was limited to an industrial survey. Manufacturers of positive and low gravity detection systems were contacted and their equipment and, in some cases, experimental concepts, are presented. The report describes each system including theory of operation, accuracy, stability, power requirements, and the gravitational environment in which the system is designed to perform.

#### CRYOGENIC TEMPERATURE MEASUREMENT TECHNOLOGY

The investigation into cryogenic temperature transducer technology was made by conducting a survey of manufacturers to establish the capability of currently available equipment to meet cryogenic system requirements. In conjunction with this survey, a literature search was conducted to identify new developments in temperature measuring techniques. The methods of temperature measuring discussed are resistance temperature transducers made from different metals as sensing elements, thermistors, and thermocouples. Also included is a discussion of measuring bridges used to determine the resistance of the temperature probe.



#### HIGH TEMPERATURE STRAIN GAGE TECHNOLOGY

Although strain measuring techniques have progressed rapidly since the development of the first strain gage, the requirements for their use have advanced much faster. This is especially true for obtaining flight load measurements on high speed vehicles operating in the earth's atmosphere.

The aerodynamic heat associated with this high speed flight can be a major cause of strain gage error. Temperatures up to 1800 F are anticipated on the aerodynamic surfaces of a Mach 6 vehicle operating at 90,000 feet. Strain gage output due to thermal stresses at these high temperatures can produce load measurement errors greater than those due to gage performance characteristics. To obtain accurate flight load measurements these errors must be eliminated in the strain gage design.

The purpose of this section of the components technology report is to review various strain sensing devices and evaluate their performance in a 1500 F to 2000 F thermal environment.



## 2.0 SUMMARY

The following is a brief review of the significant facts contained in the body of the three volume text. The summary is contained in each of the three volumes in order that the reader might have sufficient information to evaluate his need to review each volume's text in detail.

Volume I contains the following topics: Cryogenic Pressure Transducer Technology, High Pressure Flange Seals, Hydrogen Embrittlement of Transducer Materials, the Effect of Close-Coupled Versus Remote Transducer Installations on Pressure Transducers, and Techniques in Temperature Compensation of Strain Gage Pressure.

Volume II contains the following topics: Cryogenic Mass Flow Measurement Technology and Cryogenic Liquid Detection Technology.

Volume III contains two topics: Cryogenic Temperature Measurement Technology and High Temperature Strain Gage Technology.

### CRYGENIC PRESSURE TRANSDUCER TECHNOLOGY

Pressure measurements for space vehicle cryogenic systems such as for liquid oxygen and liquid hydrogen tanks, transfer lines and engine systems, have always presented a special challenge to instrumentation engineers and measurement users alike. These cryogenic liquids, especially liquid hydrogen, possess many properties which pose problems for designers. Primarily, these problems are associated with low temperature environments and with the highly volatile nature of the liquid. The most common approach to measuring pressure in these systems is to connect the pressure transducer away from the extreme low temperature environment by connecting the transducer to the sense port by a length of sense line which provides a thermal buffer for the transducer. This technique is satisfactory for only steady-state or slowly changing measurements. For oscillating or fast changing pressure systems the volatility of the liquid creates thermal dynamic oscillations and the sense line reduces frequency response both of which reduce measurement fidelity markedly.

This investigation was performed to research currently available designs which could be utilized for space vehicle applications in cryogenic systems to an accuracy of 2 percent excluding other environmental error sources.

Inquiries made to approximately 50 manufacturers resulted in seven favorable responses from suppliers indicating the availability of transducers operable with cryogenic systems of liquid oxygen or liquid hydrogen. Manufacturers responding favorably to the survey were:

<u>Manufacturer</u>	<u>Transducer Type</u>
Bell & Howell/Consolidated Electrodynamics	Unbonded Strain Gage
Bourns Inc.	Potentiometer
Dynasciences Corporation	Bonded Strain Gage
Genisco Technology Corp.	Bonded Strain Gage
Kistler Instrument Corp.	Piezoelectric
MB Electronics	Bonded Strain Gage
Statham Instruments Inc.	Deposited Strain Gage



A number of other manufacturers are known to have developed pressure transducers operable in cryogenic systems but these designs are available on special order only and thus were not included in this study primarily due to the lack of descriptive information on the instruments.

This investigation concluded that for the many application conditions of a space vehicle, none of the candidate instruments could meet the design goal of 2 percent temperature sensitivity error. Based on this conclusion, problems contributing to temperature sensitivity were investigated through research of published documents.

The single most important error source for instruments found by the researchers is the difference in temperature conditions between instrument calibration and the using temperature environment. Normally transducers are calibrated under a steady state, uniform temperature environment, usually at the liquid nitrogen temperatures. In field applications temperature gradients occur between the front face of the transducer to the aft end of the instrument. For transducers with temperature compensation provisions such as the strain gage designs, the compensation thermistors and resistors are located in the aft end of the instrument. This design alone contributes to a significant error found by one researcher to be as much as 100 percent FS for transducers that indicated less than 6 percent FS shift in standard steady state temperature tests.

A definite improvement in low temperature performance can be achieved on the part of instrument users by providing installation designs which minimize thermal gradients, such as by insulating the transducer, and by calibrating instruments under conditions of usage as closely as possible.

The conclusion of this investigation is that for applications requiring good temperature compensation, small size, low heat capacity and high frequency response with the capability of measuring both steady state and dynamic responses a new transducer design is required. Based on the information provided by researchers some design features known to provide desirable performance characteristics are: flush diaphragm design with diaphragm machined integral with the case, small case size with short body length and low thermal mass, strain gage design with gages mechanically coupled to the diaphragm in an unbonded configuration, temperature compensation circuitry located in the same thermal environment as the strain gages and transducer installation provisions which facilitate insulation provisions to minimize thermal gradients.

#### HIGH PRESSURE FLANGE SEALS

This investigation primarily addresses itself to the search for a metallic seal for cryogenic temperature and up to 5000 psig pressure applications.

The leakage rate for a seal depends on fluid properties, surface topography, pressure differential, hardness of the sealing material, and sealing contact stress.



The most important design considerations are pressure, temperature range, and type of fluid sealed. The parameters determine the bolt size, flange thickness, and materials.

Leakage is the most important criterion and most difficult to predict without tests. Many metal seals are capable of achieving leakage rates below measurable levels; however, the penalty in flange loading, extremely smooth finishes or loss of recovery, may be prohibitive. For extremely low leakage rates (less than  $10^{-8}$  scc/sec), an all-metal seal is usually required.

Seating load is an important parameter in flanged connections. The lower it is, the smaller the required flanges and bolting. Seating load is normally expressed in pounds per inch (lb/in) of seal circumference and may range from 100 to 500 lb/in, depending on the design.

Contact stress at the sealing interface partially determines leakage rate and is a function of seating load and contact area. The pressure differential across the interface, if high enough, may add or subtract significantly from the initial contact stress.

Metal seals capable of very low leakage rates must plastically deform at the sealing interface. With subsequent installations, the seal coating must try to conform to a new set of peaks and valleys and intimacy of interface is consequently reduced.

Pressure compensation, sometimes called pressure energization, pressure actuation, or pressure assistance, is the beneficial effect of pressure upon the seal contact. The geometry of many seals is such that fluid pressure augments the contact stress, thus tending to overcome the increased possibility of leakage due to the pressure. The pressure effect is negligible except at high pressures - 1000 psi or more.

Cavity requirements of the seal must provide for correct (limited) deflection of the seal, location of the seal, structural support for high pressure, and proper surface finish.

The choice of seal materials is usually determined by the operating temperature, although corrosion resistance, fluid compatibility, and radiation effects may also be major considerations. Most metal seals contain two materials, a resilient, basic-shape metal and a soft coating.

The coating material is usually a pure metal (silver, gold, nickel, or copper) or a plastic dispersion coating such as Teflon. Coating materials are chosen on the basis of softness, corrosion resistance, temperature resistance, and cost. Silver is used in the majority of low and high temperature applications and is one of the least costly.

Resilient metal seals combine the efficiency of elastomeric O-rings with the extended temperature capability of metal gaskets. The basic structural element is usually a high-strength metal, and a soft coating of metal or plastic provides the actual sealing. Like O-rings, these seals are self-energizing, have small cross sections, require light closing forces, are often reusable, and



have indefinite life. Unlike O-rings, however, they are relatively expensive, and availability is somewhat limited.

Resilient metal seals can be considered as the most promising for achieving seal integrity for high pressure and cryogenic environments. A parallel loaded joint with a groove type seal installation should provide the optimum joint configuration.

#### HYDROGEN EMBRITTLEMENT OF TRANSDUCER MATERIALS

The research work performed within the industry on hydrogen embrittlement of metals has not resulted in a clear definition of accepted standards. Because of this fact, no precise conclusions can be reached on the extent of hydrogen embrittlement as a problem for instrumentation systems. Primarily, this uncertainty results from the fact that most testing has been accomplished at 10,000 psi and pressures for liquid or gaseous hydrogen systems on Saturn S-II type vehicles are 100 psi to 1000 psi.

Generally, it is concluded that no problems exist for materials most often used for transducer construction. This conclusion is based on the experimental findings that embrittlement susceptibility increases with increasing temperature above room temperature and increasing pressure. Below room temperature embrittlement susceptibility decreases with decreasing temperature. Hydrogen has little effect on metals below a temperature of  $-321^{\circ}\text{F}$ . From the standpoint of instrumentation systems, this is favorable since the majority of measurements in hydrogen systems are made at low temperature and pressures.

The report summarizes the degree of susceptibility for various metals where data are available.

#### THE EFFECT OF CLOSE COUPLED VS. REMOTE TRANSDUCER INSTALLATIONS ON PRESSURE MEASUREMENTS

The measurement of frequency over a line length of constant diameter to which is attached a sensing transducer varies as the fundamental (fd) frequency. If the media transmitting the frequency is a gas, then the frequency is limited by the line length and the acoustic velocity. The exception to this is a situation in which the volume of the transducer cavity measuring the pressure pulse is large relative to the volume of the line. This case is called a Helmholtz resonator and it will produce an attenuation of approximately 40% over the previously noted fundamental frequency for the equivalent line length.

If frequency of pulsations of a liquid over a line is required and if the liquid is a cryogenic, a multitude of problems arise. Pressure pulses of large amplitude will produce complete distortion of phase, frequency, amplitude and signature. Small pressure pulsations will allow the passage of phase and amplitude data within the fundamental frequency range but amplitude and signature cannot be considered correct. The turbulence produced by the

pressure pulsations forces the liquid down a gas filled line where it expands due to the sudden temperature gradient. The resultant change in momentum of the mass of cryogenic liquid in motion and the volume change produces an overall distortion of the output.

The accurate measurement of fidelity of a cryogenic liquid can only be obtained by using either a close coupled or flush mounted transducer. The ideal installation is that of mounting a pressure transducer diaphragm directly against the media to be measured. If this is not possible then the sensor can be boss mounted off a fitting. Care must be taken in the last instance in that a short run from the liquid to the sensor diaphragm might form a Helmholtz resonator.

#### TECHNIQUES IN TEMPERATURE COMPENSATION OF STRAIN GAGE PRESSURE

The classic techniques for compensation of pressure transducers to temperature sensitivity is to select materials with desirable performance characteristics and to apply compensating resistors and thermistors to the bridge circuitry. These techniques compensate for zero shift and sensitivity changes.

Manufacturers can further improve transducer performance by locating the resistors and thermistors in the same thermal environment as the temperature sensitive member. Instrument users can insulate instruments to stabilize temperature and can apply corrections to calibration curves for zero shifts determined from a reference pressure test.

#### CRYOGENIC MASS FLOW MEASUREMENT TECHNOLOGY

The object of the cryogenic flow study was to establish the state-of-the-art and to recommend either a specific flow system or if that was not possible, to establish a direction for future development.

The measurement of cryogenic mass gas flow depends upon the determination of several variables. If the measurement is made either inferentially or directly, a compensation of variables must be taken into consideration. Density is always common to an inferentially mass measurement with either a velocity or velocity squared measurement required. Since density itself can be a function of pressure, temperature, torque or damping ratio an inferential measurement of flow can consist of a great deal of variables; some of which can cover a large range. In the direct measurement of mass flow the output can be a measurement of linear or angular momentum or heat transfer. Although the output can be a single variable the mechanism required to generate the output can be extremely complex and limited in range. In addition to the above noted problems, there are a number of material, installation and design problems that also must be solved.

The initial 62 manufacturers reviewed were reduced to 16 candidate systems. These candidate systems consisted of six true mass flow meters and eleven inferential mass meter systems. In addition to manufacturers of flowmeters, such associated problems as facility calibration and previous



data were reviewed. After analyzing all candidate systems, previously run test data, test facilities and the National Bureau of Standards at Boulder, it was concluded that no flowmeter had a proven history of meeting the requirements. Two system types looked promising -- the turbine-capacitance densitometer inferential meter and the heat transfer mass momentum meter. Of these two systems, only the inferential turbine candidate had some data at a cryogenic gas temperature and hence is the recommended choice.

#### CRYOGENIC LIQUID DETECTION TECHNOLOGY

This section covered twelve propellant gaging systems offered by nine manufacturers. Five of the systems are applicable to positive g applications and seven are applicable to both positive and zero g usage. These systems can be further categorized into five basic operating principles. These are point sensor, capacitance probe, radio frequency, infrasonic, and nucleonic systems. Point sensors and capacitance probes are only useful in positive g environments. The infrasonic and nucleonic systems are applicable in zero g environments, however, both designs are still in the development stage and at this time impose a high weight penalty to obtain good accuracy.

The use of the more standard coaxial cylinder capacitance sensor system for continuous gaging of propellants is not practical due to the capillary rise that occurs at low gravity conditions. The capillary rise for LH<sub>2</sub> and LOX is on the order of 40 and 20 inches respectively for capacitance sensors similar to those used in the Saturn S-II stage.

Since future space vehicles operate under both zero g and positive g environments, no single concept of propellant gaging provides the desired accuracy under both conditions. The results of the study indicate that the radio frequency system is best for propellant monitoring during zero gravity periods when propellant tanks are less than half full. During periods of positive g the discrete level sensing system offers the best accuracy especially during propellant loading and for monitoring the liquid level with tanks full. The best design compromise appears to be a system utilizing both the RF system and discrete level sensors for all phases of the vehicle operation.

#### CRYOGENIC TEMPERATURE MEASUREMENT TECHNOLOGY

Commercial cryogenic thermometers are available which are capable, under carefully controlled conditions, of precisions greater than  $\pm 0.05$  K. However, such precision can only be obtained under static or quiescent conditions. When thermometers are required to respond to rapid temperature fluctuations such as occur in the cooldown of propellant lines, the indicated temperature may depart significantly from the "true" temperature. The loss in validity of the measurement does not reflect a degradation in accuracy of the temperature sensor, but rather indicates that the temperature of the sensor is not at all times the same as the surroundings.

The terms "accuracy" and "reproducibility" require some explanation pertaining to temperature transducers. Accuracy is the significance with which the thermometer can indicate the absolute thermodynamic temperature. This includes errors of calibration as well as errors due to nonreproducibility. Reproducibility is the variability observed in repeating a given measurement using



different thermometers of the same type. Changes produced by thermal cycling of the thermometer to and from ambient are also included in this parameter.

Temperature sensor materials can be divided into three categories: pure metals, non-metals, and thermoelectric devices called thermocouples. While there exist a number of pure metals that are more or less suitable for resistance thermometry, platinum, primarily because of many favorable characteristics, has become predominant as a temperature measuring element. Desirable features such as ready availability in high purity and extensive knowledge about platinum's behavior down to 20 K have tended to perpetuate its use. Its principal disadvantages are low resistivity and insensitivity below about 10 K.

Copper, nickel and tungsten have also been exploited as temperature sensing elements. Copper is inexpensive and has a very linear temperature/resistance relationship. Copper has poorer stability and reproducibility than platinum and its low resistivity is undesirable when a high resistance element is required for temperature measurements below 100 K. Nickel is widely used over the temperature range of 170 K to 575 K; however, this report was primarily concerned with temperatures below 100 K and at this temperature, very little work has been done with nickel. Tungsten sensors are less stable than other metal sensors because full annealing is impractical. At low temperatures the percentage change in resistance per degree is much less than platinum. Tungsten's great mechanical strength allows extremely fine wires resulting in convenience for manufacturing sensors having high resistance values, but this is not important unless the probe resistance must be larger than 5 or 6 thousand ohms.

Non-metals such as semiconductors, carbon resistors, and thermistors are used as temperature sensing devices in the laboratory with some advantages over pure metals. The greater disadvantages for their usage on a space vehicle within the temperature range of 0 to 100 K tend to discount them as a serious consideration unless further development and knowledge is pursued.

Germanium semiconductors are available from several commercial sources. The sensing element is a small single crystal with high resistivity. The resistance/temperature relationship is very complex and requires many calibration points when used over a wide temperature range. The reproducibility is poor and thermal cycling causes some drift to occur. This affects their interchangeability drastically.

Carbon resistors have been used as temperature sensors at extremely low temperatures. Carbon has a high sensitivity in the temperature range of 0.1 K to about 20 K; however, above 20 K the  $dR/dT$  is very unstable.

Thermistors are inexpensive and very sensitive to temperature. They are small in size and have a high resistivity. Thermistors have a nonlinear R-T relationship and poor stability. Because of the nonlinearity, numerous calibration points are required. A single thermistor is generally unsuited for wide temperature spans because its resistance goes from values which are so high to be inconvenient to values which are too low to be measured with conventional signal conditioning equipment. Several thermistors must be used to cover a wide temperature span.



Thermocouples in comparison with other temperature sensors have certain advantages. The temperature sensitivity span can be small, and is more flexible for installation. The thermocouple is a device of comparatively low cost, high accuracy, wide measurement range, fast thermal response, ruggedness, and reliability. Some of the more obvious disadvantages are the very low output voltage requiring more complex and costly signal conditioning equipment, and the homogeneity of the materials used to manufacture thermocouples is such that interchangeability without complete recalibration is impractical.

After an objective analysis of the different methods of temperature measurement in the 20 to 100 K range, the wire wound metal, especially platinum, is best suited for measurements where high accuracy and stability is required. The thermistor is best for point measurements and the thermocouple best for high temperatures or for rough indication of temperatures.

Resistance bridges are used as a comparison device for measuring precise resistance ratio relative to temperature change of a platinum thermometer. In making comparison resistance measurements for attainment of a high degree of precision, of the order of 1.0 PPM, the following design considerations should be evaluated when selecting a particular bridge design: effects of lead resistance, thermoelectric emf's, self-heating, reactance, bridge linearity, noise, interaction, bridge sensitivity, and accuracy.

From the numerous available bridge designs, a designer has to determine as to which of the bridge designs is most suitable for use for a particular design application. Therefore, in order to establish a methodical design approach, these numerous bridges are described in its basic form as either a full or half bridge. These basic bridges are then evaluated for its advantages and disadvantages based on applicable design considerations. In the process of evaluation, these basic bridges are reconfigured for use as either symmetric or asymmetric configuration and as a low level or high level bridge output based on the importance of a particular design consideration. A table depicting the advantages and disadvantages relative to the various design considerations has been prepared to provide direction in the design approach.

Lead resistance is widely accepted as a major problem in a temperature measurement system design. Because of this problem, numerous bridges such as Mueller, Smith, Siemens and numerous others have been developed since 1871. Each bridge has merits in leadwire resistance compensation, and therefore each is discussed in this report. Variations used in these bridges can then be adapted to the basic bridge selected for the best lead resistance compensation.

#### HIGH TEMPERATURE STRAIN GAGE TECHNOLOGY

The objective of this section of the components technology report was to review current strain sensing devices and evaluate their performance in a 1500 F to 2000 F airborne thermal environment. The evaluation consists of comparing gage principles of operation, gage materials, gage attach methods, installation techniques, performance characteristics and gage availability.



A literature survey was conducted which resulted in the selection of three strain sensing devices for evaluation:

- a. Electrical resistance strain gage
- b. Electrical capacitance strain gage
- c. Thermal-null strain sensor

The resistance strain gage operates on the principle that when a load is applied on any material, that material will expand or contract causing strain within the material. If a grid of wire is bonded to the material, it will stretch or be strained exactly as the surface of the test material is strained. This stretching and compressing of the grid wire causes a change in the electrical resistance of the wire which is proportional to the strain in the test member.

One of the major contributors to errors in high temperature strain gage applications is the effects of apparent strain. In a resistance gage, apparent strain causes a change in resistance of a mounted gage due to a change in temperature without an applied load on the test specimen. In an effort to reduce this apparent strain error, temperature compensation is included in the gage designs.

Many resistance gage alloys have been tested in an effort to extend the upper temperature limits. Most alloys exhibit a solid solution phase change below 1200 F. This phase change causes an anomaly in the resistance vs. temperature curve and yields an unsatisfactory alloy for high temperature strain gage usage. Platinum-tungsten alloys are currently the best available for high temperature resistance strain gages.

Attachment of high temperature resistance strain gages can be accomplished by using ceramic cement, aluminum oxide flame spray or by welding. The method used depends upon the material of the test specimen.

There are many resistance gages on the market today. However, only a relative few advertise the capability of operating at 1500 F and none at 2000 F.

Since 1968, Hughes Aircraft, and Wright Patterson Air Force Flight Dynamics Laboratory have coordinated on the development of a high temperature capacitance strain gage. This gage operates on the principle that variations in the gage dimensions caused by strain in the test specimen will change the capacitance of the gage. This change in capacitance is then directly proportional to the strain in the test specimen. The configuration selected for the capacitance gage was a parallel plate gage mounted in a rhombic frame. The gage consisted of a capacitance wafer containing stainless steel plates with mica dielectric insulators mounted in a stainless steel rhombic stress frame.

### 3.0 CRYOGENIC FLOW MEASUREMENT TECHNOLOGY

The measurement of mass flow depends on accurately determining a number of variable parameters. These variables include temperature, pressure, torque, velocity, rangeability, momentum, heat transfer and density. Although it is not required to determine each of these variables for every problem, they are used in combinations. In addition to these parameter variables, there are a number of materials, installation and detail design problems to solve. In the situation where the flowmeter is placed in series with the system under study, seal materials must be carefully chosen as conditions of wear, corrosion and abrasion may change the flow characteristics and the meter's calibration. As bearing friction changes or surface heat transfer coefficients vary, the empirical relationships fail or become less accurate. Extremely low temperatures present a structural problem in design and in assembly and subsequent interference due to tolerance buildup. If these variables are held to a minimum, the relative ease of the measurement increases proportionally.

The study requirement is to determine mass gas flow at a cryogenic temperature such as encountered in a cryogenic propellant tank vent system to an accuracy of 1% or better. If we assume that the propellant tanks contain hydrogen and oxygen and that the vehicle using them is in earth orbit, we have a practical application of the requirement. The achievement of this flow requirement is extremely difficult because it involves a number of measurement parameters as noted above and the range of these parameters is wide. The temperature range and flow rates would be large in such an installation especially when using cryogenic hydrogen gas whose volume change would be close to 3 to 1. It would also be mandatory to have a rapid response capability in order to handle transient changes accurately. During the study period, every flow measurement device and most of the variations of a type were reviewed. Vendor and government sources were included in this review which consisted of a literature search, vendor telephone conversations and facility tours. The results of this survey produced no mass flowmeter design that had a record of meeting the study requirements. The reason for the lack of data on the requirement was that the use of such a broad range of measurement variables had never been attempted before. Most flowmeter designs had been specifically designed and calibrated for use in a less demanding application. In such a case, forcing such media variables as temperature and pressure to be at a constant value before being measured, the problem of measuring mass flow could be simplified to the measurement of velocity and the use of a thermophysical chart of the media to determine density. The Quantum Dynamics turbine flowmeter system design showed promise in meeting all the design parameters but even it did not have sufficient data to establish its capability with high confidence. [A] Fifteen other candidate systems offered an ability to measure some portion of the total number of parameters necessary in meeting the range requirements. In some cases, two or three of these systems could be used in parallel to give an output over the total range required.

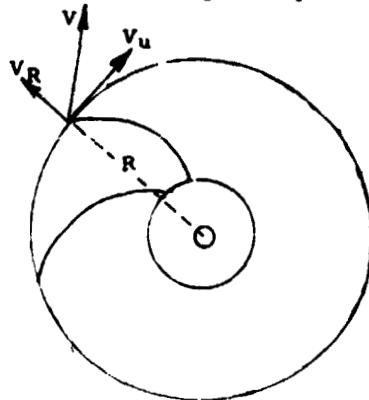
### 3.1 TECHNICAL DISCUSSION

In the measurement of mass flow, the basic types of flow systems and parameters to be measured must be defined and understood. All of the parameter variables, with the exception of rangeability, will become clear as the types of designs are discussed. Rangeability is the ratio of the highest velocity to the lowest velocity of the flowing media. The highest velocity occurs at the largest mass flow rate and the lowest density while the lowest velocity is a function of the smallest mass flow rate and highest density. Since density of a media is a function of temperature and pressure range, rangeability can be considered as proportional to the ratios of temperature, pressure and velocity. In the case of hydrogen gas, if the pressure is maintained constant and temperature varies over a relatively wide span of 56 K, the density change can be a 3 to 1 change. Combining this with a mass flow rate from 1 to 5 lbs/second gives a rangeability of 15 to 1. This is not considered high unless you plan to use an angular momentum type flowmeter in which case its upper limit is approached. The following is a description of the two basic flowmeter designs: (a) The inferential meter and (b) the true mass flowmeter. There are a multitude of variations on these two basic designs but only those five types included in the sixteen candidates are discussed. Three of these types were inferential mass meters while the other two were true mass meters.

- a. Inferential Mass Meter- This mass flowmeter design can also be called a mass metering system since it requires the combination of two inputs one of which is density ( $\rho$ ) and the other input is velocity squared ( $V^2$ ) or velocity ( $V$ ). The drag body candidate design in which a drag target is deflected by the flow media is an example of velocity squared ( $V^2$ ) measuring device. Since force ( $F$ ) is equal to the coefficient of drag ( $C_D$ ) times the area ( $A$ ), the density ( $\rho$ ), the velocity squared ( $V^2$ ) divided by two times the acceleration due to one gravity and if ( $g$ ),  $C_D$ ,  $A$  and  $2g$  are known constants, then the output, force ( $F$ ) can be reduced to density ( $\rho$ ) times velocity squared ( $V^2$ ). In the turbine design, volumetric flow is a function of the turbine rotor speed. Velocity ( $V$ ) is measured directly as the turbine blade tip, under movement by the flowing media, passed either a radio frequency or magnetic pickoff. The pulse output then becomes a direct measurement of flow. The output, velocity, or velocity squared of these two variations are multiplied by density ( $\rho$ ), the resultant being mass flow rate ( $M$ ). The computation and hence the necessary electronics are somewhat more complex for the reduction of  $V^2$  than  $V$ . By far, the most popular system and type is the velocity ( $V$ ) indicator and in particular, the volumetric turbine in combination with a density measuring device. The density measuring device itself is an equal factor in measuring inferential flow accurately. It can be approached in several different ways. Some of the most notable of these ways are the capacitance-dielectric, the pressure-temperature-data table (P-T-D), the nuclear radiation types (beta and gamma), the oscillator drag body (damping), and the velocity of sound and microwave transmission characteristics approach. (2) All but the "P-T-D" approach can be called

"densitometers" because there is no manual reference necessary, the output can be in a direct voltage proportional to density. The most widely used type of densitometer is the capacitance type in which the dielectric constant of the flowing media is measured. These devices usually are so designed as to also act as a flow-straightener. A series of cylinders within cylinders straightens and insures laminar flow while the gap between these circular capacitance plates measures the variation in dielectric constant. Laminar flow is defined by a Reynolds number ( $Re$ ) less than 2000. Reynolds number is a dimensionless ratio of inertia forces divided by viscous forces and low or no turbulence allows the measuring of very low flow accurately. Flow straighteners are not necessarily as important to other types of inferential mass meters as to the turbimeter. The total inferential mass meter system requires a velocity or velocity square measurement, a density measurement physically located at or near the velocity measurement and in some cases, a suitable flow straightener to produce laminar flow.

- b. True Mass Flowmeter - There are two types of true mass flowmeters, both of which work on different principles. The first is the momentum type, both angular and linear, and the second is the thermal mass meter. The angular momentum mass flowmeter utilizes the rate of change of fluid angular momentum to generate a torque proportional to mass flow. Rotating motion at a right angle to stream flow is imparted to the flowing media by means of a turbine. The media torque ( $T$ ), the media angular velocity ( $\omega$ ) are related to mass flow ( $\dot{M}$ ) by the expression,  $\dot{M} = T/\omega$



Components of  $V$

$V_R$  = radial component of  $V$

$V$  = tangential component of  $V$

$$F = \dot{M}a = \dot{M} \frac{dV}{dt}$$

multiplying by radius ( $R$ ) to get moment of momentum ( $T$ )

$$RF = T \text{ (torque)} = \frac{d}{dt} (\dot{M}/\omega r) = \text{rate of angular velocity}$$

$$T = \dot{M}\omega$$

$$\text{therefore } \dot{M} = T/\omega$$

From this expression, it can be seen that a measurement of mass flow can be obtained either by (1) holding the turbine speed constant and measuring variation in torque  $\dot{M} = T/k$  or  $\dot{M} \propto T$ , sometimes called an



The Bendix facilities are quite large and extensive. They have their own calibration facility for liquid cryogenics. Their engineering staff is also involved in zero g propellant management studies. [10]

Potential options for future space vehicle use should center around the force screen drag body concept in use with a densitometer although the angular momentum device offers promise for further development. It would require extensive design in the area of the pickoff in order to withstand any excessive g load environment.

Advantages of this type of drag body system are fast response, a low pressure drop and essentially no moving parts. The disadvantages that are unique to the Bendix force-screen flowmeter are the need for a density measurement, further development, especially in the area of flight vehicle usage and redesign for high g force environment. In addition, very little information is available on cryogenic operation at LH<sub>2</sub> temperatures. As for two phase or cryogenic gas mass flow near but below the boiling point of O<sub>2</sub> or H<sub>2</sub>, no test data are available.

### 3.3.2 Cox Instruments Division of Lynch Corporation

Cox manufactures only one cryogenic flowmeter and it is a type one, turbine and pickoff design. In addition, they manufacture two other designs, the "rotometer" and the variable reluctance spring loaded force spool meter. They are primarily noted for the manufacture of primary weight type flow calibration benches. Those standards are used by the Air Force and others for calibration of fuel flow meters such as used on aircraft. They are not suited nor intended for cryogenic uses but illustrate manufacturing capability.

The Cox turbidimeter consists of a free-moving suspended rotor and a signal pickoff. Fluid or gas flowing through the meter makes the rotor turn at an angular velocity directly proportional to the rate of flow. As the rotor turns, the blades induce an alternating current in the signal pickoff. The frequency of this signal is calibrated to be proportional to the rate of flow. An electrical coil, contained in the modulated carrier pickoff, forms part of a tuned high frequency oscillator circuit. As each rotor blade passes the pickoff, a change in coil reluctance occurs, resulting in amplitude modulation of the carrier signal. A signal conditioner supplies the carrier signal to the pickoff and translates the resulting modulated signal into a constant 5 volt amplitude square wave with frequency proportional to volumetric flow rate. The strength of the signal improves signal to noise ratio and permits long distance transmission.

In addition to the pickoff and the rotor assembly, the flowmeter body contains the inlet and outlet flow straighteners and the hub and bearing assembly. The flow straightener design used by Cox consists of six equally spaced vanes rotating out to the periphery of the body housing. The bearings are of the miniature ball type and are 440 c CRCS. [11]

the transition point from liquid to gas and the cryogenic gas remains in a gaseous state? (2) What are the heat transfer characteristics and problems associated with measuring thermal differential at a cryogenic temperature near that of the liquid state? (3) What work has been done, and what work is planned to be done to establish actual values of mass gas flow at temperatures in the 33 K (-400 F) to 68 K (-300 K) range?

The report that follows in the main body of the text is a composite of information gathered while the requirement for measuring liquid hydrogen and oxygen only was established. The information, conclusions and possible solutions to measuring gaseous hydrogen and oxygen flows are presented. The approach that will be taken in this report will be to review the data that has been made available, to apply that data to a specific use, and offer suggestions for future development work.

### 3.2 FLOW MEASUREMENT DESIGN CONSIDERATIONS

In addition to the consideration that must be given to the previously mentioned variables, accuracy requirements, practical application limitations and test facility calibration must also be included in any design. All these elements must be weighed against each other in order to arrive at the most practical solution to a particular problem. The problem under consideration is one of measuring very accurately the mass flow of gaseous hydrogen or oxygen over a large cryogenic temperature range. The flow rate can vary from very low to very high, thereby establishing a very wide rangeability. One variable, pressure can be held at a minimum and relatively constant value. Since the propellant tank would have to be large and light weight structural integrity would dictate the restriction of pressure in the tank to less than 100 psig. This could be accomplished with close tolerance pressure switches. Various approaches to the range problem would be to use more than one flowmeter to cover a greater range or pickoff a small proportionate part of a larger flow and measure it. Force the flowing media to conform to a state in which several variables are fixed as constants such as pressure and temperature. Then measure turbine rotor speed (V) and multiply it times the media density ( $\rho$ ) at that temperature and pressure.

Practical application limitations must take into consideration such things as power availability, space and environmental requirements. Some of the above noted approaches may not be practical to implement due to lack of space or a weight penalty problem. The availability of power to run such a system could also be a very limiting problem.

Finally, the availability, cost and accuracy of either developing or finding a suitable test facility to use may be the greatest design consideration challenge of all. At present, no primary standard calibration facilities capable of measuring gaseous cryogenic mass flow exist. Two possibilities presently exist as potentially able to meet a variety of flow rate requirements. Both are located in the State of Colorado. One is located just outside the city of Munn in an old "Atlas E" launch site and could probably be modified to handle cryogenic gases.<sup>(4)</sup> The other is located at the National Bureau of Standards facility in Boulder.<sup>(5)</sup> Tests are being run currently with hydrogen gas, at ambient temperatures, with future tests planned for this facility at low temperatures and greater flow rates.

### 3.2.1 Densitometer Designs and Concepts

Where a mass flow measurement is made inferential, density must be determined. This can be done in several ways. Probably the most widely used and the most straight forward approach is to take a temperature and pressure reading and compare them with a density readout using a thermophysical properties data sheet for the particular media under study. The primary disadvantage in this approach is the need for manual manipulation. In addition, the temperature and pressure sensors must be accurately calibrated and stable with time, mechanical strain and changes in the environment. Although this method of density measurement does not really constitute a densitometer per se, it is a commonly used practice in measuring mass flow. The need to transmit data via telemetry results in this technique not being applicable to its use by an orbiting vehicle.

Five other techniques that can be used to measure density and for which data is available truly fit the definition of a densitometer. In each case, these techniques result in an output directly proportional to density and require no manual data interpretations. As in the flowmeter itself, all the associated problems of calibration and specific tailored results are unique to each type of densitometer design. An inferred mass flow accuracy is dependent upon the accuracy of the required individual measurements. In the case of the fluid density measurement, the accuracy can be difficult to determine since density is calibrated in a static state but used in a dynamic one. When the initial calibration is made, no flow conditions exist. However, in use, density may be a moment to moment variable.

These techniques are (1) the dielectric change in a fixed capacitor, (2) the vibrating vane, (3) the measurement of attenuation of gamma rays or the count rate of beta particles reading of a nucleonic detector, (4) the measurement of the velocity of sound using two quartz crystals as transmitter and receiver, and finally (5) the propagation of a microwave signal in a homogeneous medium described by the attenuation constant and the phase constant.<sup>(6)</sup> Both of these are functions of the complex dielectric constant and hence, the density of the medium.

Of the six density measuring methods, three are not sufficiently developed or have intrinsic problems in their design. These three, the nucleonic attenuation, the ultrasonic and the microwave are not inferential mass candidates densitometers. The temperature-pressure method is not a densitometer per se in that it does not read out in real time. The remaining two, the capacitance to density approach and the vibrating vane all have had previous data to establish their validity and are presently in use by candidate flowmeter manufacturers. Only the capacitance to density method has been used successfully to measure a cryogenic gas density although the data available is over a relatively short period of time.

### 3.3 SURVEY RESULTS OF AVAILABLE DESIGNS

The total number of flowmeter manufacturers surveyed was sixty-two (Table 3.6.1). These were reduced to a final sixteen candidates (Table 3.6.2). These sixteen manufacturers range in capability from those that manufacture complex momentum meters to those who fabricate the relatively simple thermal meter.



Rosemount Engineering was included in the following detailed review based on their past performance on the Apollo Program.[7][8] They presently do not manufacture a gaseous mass flowmeter. One other manufacturer, Electro Development Corp., does not presently manufacture a cryogenic flowmeter, but their new design has been formally proposed as capable of meeting cryogenic flowmeter requirements.

Each of these sixteen manufacturers are discussed in detail with the following points being covered:

- . Type and design of system or systems
- . Inferential or true mass measurement
- . Type and design of densitometer used if an inferential system
- . Potential capability of measuring cryogenic mass gas flow and required effort to meet this potential
- . Disadvantages and advantages of each system(s)

The study by North American Rockwell personnel involved primarily a literature search and data survey with no hardware being procured or tested. Five of the sixteen candidate facilities were visited while the other eleven were evaluated as to experience and capability using their literature.

The sixteen candidate designs can be broken down into five types for analysis. Type one is the turbine and pickoff. As the turbine is rotated past the pickoff, it registers or induces a signal in the pickoff measurement to give mass flow ( $\dot{m}$ ). Type two, the drag body, immerses a bending body with a target in the flow stream. A strain gage attached to the cantilevered beam changes a balanced bridge in proportion to strain. Density ( $\rho$ ) is needed to produce mass flow rate. Type three is a bluff body inserted into a flow stream. The sensor, which is embedded into the bluff body face, consists of a pair of electrically self heated thermistors whose temperature and resistance vary with the localized flow oscillations. Output is in the form of a pulse train, frequency proportional to volumetric flow, and the additional measurement of density must be made in order to give mass ( $\dot{m}$ ) flow output. Type four measures mass flow directly. A true direct mass flow rate is obtainable with only one measuring device. In one case, an oscillating drag body produces a damping torque. The sensor damping ratio  $\zeta$  is directly proportional to mass flow rate ( $\dot{m}$ ). The angular momentum flowmeters are also type four and measure mass flow directly. They use the basic principal of measuring the torque of a rotating element. Torque is equal to mass flow rate times the difference in impeller radii multiplied by the angular velocity. Type five, the thermal mass flowmeter, also measures mass flow directly. Heat rate transfer to the following media is compared to that of a heat sink or the no flow condition.

The flowmeter candidate systems are discussed in the following section presented in vendor alpha/numerical order:

Section 3.3.1	The Bendix Corporation
3.3.2	Coz Instruments
3.3.3	Eastech Inc.
3.3.4	Electro Development Corp.



Section 3.3.5	Fisher and Porter
3.3.6	Flow Technology Inc.
3.3.7	Foxboro Instrumentation
3.3.8	General Electric Co.
3.3.9	Hasting-Raydist
3.3.10	Honeywell Inc.
3.3.11	ITT Barton
3.3.12	Quantum Dynamics Inc.
3.3.13	Ramapo Co.
3.3.14	Rosemount Engineering Co.
3.3.15	Simmons Precision
3.3.16	Thermo-Systems Inc.

#### 3.3.1 The Bendix Corporation, Instruments & Life Support Division

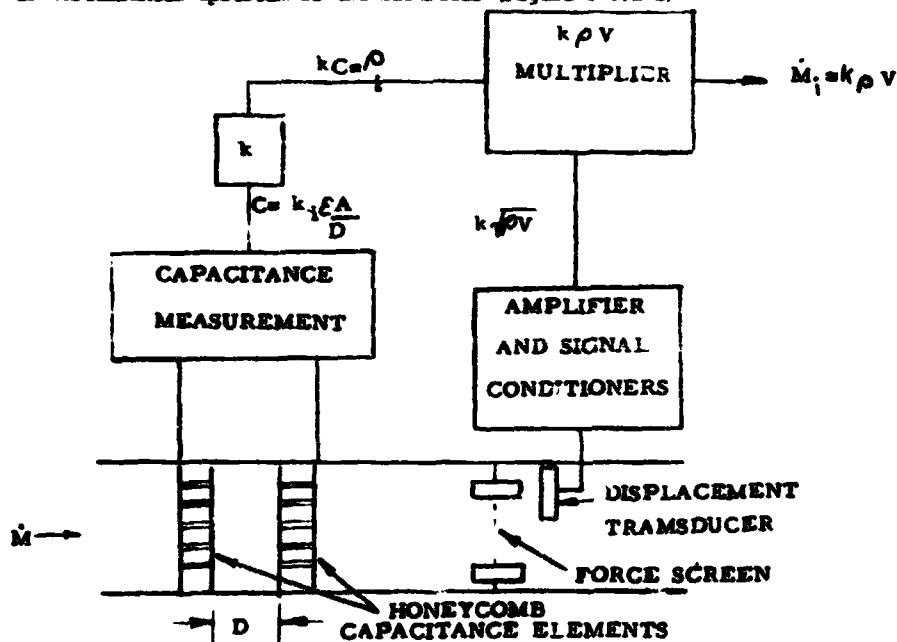
Bendix's candidate flowmeter is a type two drag body flowmeter that inferentially measures mass flow. It is used with a capacitance measurement to give an inferential mass flow output reading. The system employs a force re-balancing scheme in which the screen drag force is balanced against a force applied by attracting electromagnets. The change in dielectric constant is related to density and is obtained by monitoring a flow through capacitor placed in the flow stream.[9]

In addition to the drag body, two other designs are manufactured and commercially sold. One, the variable area flowmeter, uses the force exerted by the flowing media against a spring-restrained, rotating vane within the metering chamber to balance the force of a calibrated torque spring. The vane assumes a definite angular position which is proportional to flow rate. The second design is an angular momentum mass flowmeter and it is unique in that it does not contain a motor imparting angular momentum to the flowing liquid. It consists of two turbines, a drive-turbine and a reaction-turbine, mechanically coupled through a spiral spring which acts as a constant weighing mechanism. The entire turbine assembly rotates freely, however, the spring restricts displacement of one turbine to the other to less than one revolution, the reaction turbine lagging the drive turbine. The amount of lag is a function of flow rate.

Of the three designs, only the inferential force screen meter is rated by Bendix as a cryogenic mass gas or liquid flowmeter for use with hydrogen or oxygen. The other two systems are referenced for two reasons. One reason is that they illustrate Bendix's capability and another is that the angular momentum type has definite possibilities for use as a true mass flowmeter in cryogenic application. It was a simplified derivation from a partially successful previously designed cryogen mass flowmeter for  $LH_2$  and  $LO_2$ . The construction was much more complex because the drive turbine was motor driven rather than fluid driven and was actually submerged in the flowing cryogen stream. The need to use seals and complex met. is of bringing the electrical leads from the submerged motor to the outside presents problems. These, as well as starting torque ability at low temperatures, required abandonment of the project after minimal success. This concept does warrant further study and is mentioned in passing for the reader's information.

The force screen flowmeter, when coupled with a densitometer, measures mass flow for cryogenic liquids, gases and transition points. Two measurements of a fluid flowing through a pipe are made, the integrated drag force exerted on a wire screen placed in the flow stream and the density of the fluid. The system employs a force-rebalancing scheme in which the screen drag force is balanced against a force applied to attracting electromagnets. In dielectric fluids, the dielectric constant is related to density by the Clausius-Mossotti relation. The density measurement is obtained by monitoring the dielectric constant of the fluid with flow-through capacitors placed in the flow stream. The electronic servo then multiplies the two signals (density and drag force) to obtain true mass rates of flow.

In this type of design, the honeycomb density plates also act as flow straighteners to insure a laminar flow condition and to eliminate as much as possible of the angular velocity components which might have been imposed upon it due to disturbances upstream of the flowmeter (Figure 3.3.1-1).



$C$ =Capacitance	$\rho$ =Actual density
$D$ =Distance between capacitance element	$\rho_i$ =Indicated density
$A$ =Area	$V$ =Velocity
$\epsilon$ =Dielectric constant	$k$ =constant
$k_1$ and $k$ are constants	$\dot{M}$ =Actual mass flow rate

[9]

Figure 3.3.1-1 The Bendix Inferential Mass System



The Bendix facilities are quite large and extensive. They have their own calibration facility for liquid cryogenics. Their engineering staff is also involved in zero g propellant management studies. [10]

Potential options for future space vehicle use should center around the ion screen drag body concept in use with a densitometer although the angular momentum device offers promise for further development. It would require extensive design in the area of the pickoff in order to withstand any excessive g load environment.

Advantages of this type of drag body system are fast response, a low pressure drop and essentially no moving parts. The disadvantages that are unique to the Bendix force-screen flowmeter are the need for a density measurement, further development, especially in the area of flight vehicle usage and redesign for high g force environment. In addition, very little information is available on cryogenic operation at LH<sub>2</sub> temperatures. As for two phase or cryogenic gas mass flow near but below the boiling point of O<sub>2</sub> or H<sub>2</sub>, no test data are available.

### 3.3.2 Cox Instruments Division of Lynch Corporation

Cox manufactures only one cryogenic flowmeter and it is a type one, turbine and pickoff design. In addition, they manufacture two other designs, the "rotometer" and the variable reluctance spring loaded force spool meter. They are primarily noted for the manufacture of primary weight type flow calibration benches. Those standards are used by the Air Force and others for calibration of fuel flow meters such as used on aircraft. They are not suited nor intended for cryogenic uses but illustrate manufacturing capability.

The Cox turbidimeter consists of a free-moving suspended rotor and a signal pickoff. Fluid or gas flowing through the meter makes the rotor turn at an angular velocity directly proportional to the rate of flow. As the rotor turns, the blades induce an alternating current in the signal pickoff. The frequency of this signal is calibrated to be proportional to the rate of flow. An electrical coil, contained in the modulated carrier pickoff, forms part of a tuned high frequency oscillator circuit. As each rotor blade passes the pickoff, a change in coil reluctance occurs, resulting in amplitude modulation of the carrier signal. A signal conditioner supplies the carrier signal to the pickoff and translates the resulting modulated signal into a constant 5 volt amplitude square wave with frequency proportional to volumetric flow rate. The strength of the signal improves signal to noise ratio and permits long distance transmission.

In addition to the pickoff and the rotor assembly, the flowmeter body contains the inlet and outlet flow straighteners and the hub and bearing assembly. The flow straightener design used by Cox consists of six equally spaced vanes rotating out to the periphery of the body housing. The bearings are of the miniature ball type and are 440 c CRBS. [11]



As the turbine output is in volumetric (V) flow a density ( $\rho$ ) measurement is necessary in order to provide mass flow rate (M). Cox does not make a densitometer and requires that the customer provide his own density measuring system.

Potential capability depends upon the development of a bearing design which could withstand long periods of "dry" operation and the establishment of suitable calibration facilities or corresponding test results.

The calibration facilities at Cox were oriented toward hydrocarbon fuels and no facilities for cryogen calibration were available. Calibration facilities using water as the media were available; however, the position that a transfer or "k" factor is applicable to convert these data to a cryogenic equivalent is highly questionable even within an acceptable tolerance ( $<5\%$ ). [12]

The advantages of Cox's turbine flowmeter are typical to any of the other seven turbine candidates. Several manufacturers use RF pickoffs rather than magnetic which in itself is only an advantage over magnetic drag at low speeds. Turbinometers are highly repeatable regardless of installation position, lightweight and compact in size, and the output signal is digital. They require only a short straightening section and have a long history of successful cryogenic use. Their major disadvantages are that they need a density measurement for inferential mass flow and bearing wear due to overspin or gas flow may present a problem. A comparison of errors for each type of meter is made in section 3.6.3.

#### 3.4.3 Eastech, Inc.

A delta shaped bluff body type three flowmeter is installed with the base of the delta facing upstream. Fluid vortices are formed against the bluff body and shed off its downstream face in a regularly oscillating pattern. The frequency of oscillation is directly proportional to volumetric flow rate, for either liquids or gases. Vortex shedding frequency is sensed by a pair of glass covered thermistors embedded in the upstream face. The thermistors are electrically heated to a temperature above that of the flowing stream, and sense the cooling effect of the vortex shedding by changes in temperature, and therefore resistance. Output is in the form of a pulse train, frequency proportional to volumetric flow.

The Eastech bluff body flowmeter output is proportional to volumetric flowrates and since it requires the measurement of density, it is another example of an inferential mass flow meter. This type of meter is defined by the equation:

$$F = AC_D \rho \frac{V^2}{2g}$$

This output reduces to  $\rho v^2$  and must be inferentially combined with the addition of a densitometer measurement to provide mass flow output as shown by:

$$\rho \frac{V^2}{2g} = v^2 \qquad \sqrt{V^2} = V \qquad \rho V = \dot{M}$$

The manufacturer's literature claims working temperatures from "+400 F to Cryogenic" and "any and all liquids, gases or slurries".

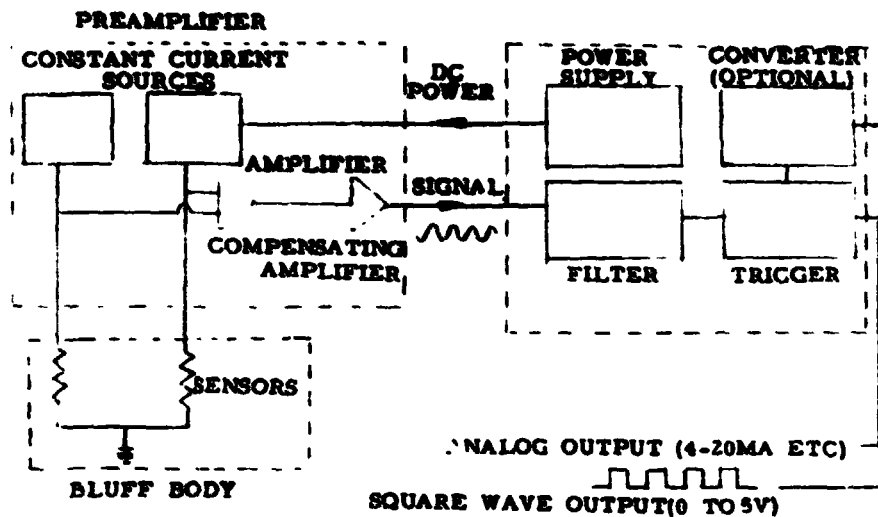
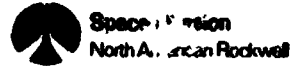


Figure 3.3.3-1 [3] The Eastech Bluff Body Schematic

A good deal of information was noted as to capabilities in minimum and maximum flow rates of gases and liquids at 60 F; however, no information was found as to this type of flowmeter in actual operation at a cryogenic liquid (LN<sub>2</sub> or LO<sub>2</sub>), a cryogenic gas (H<sub>2</sub> or O<sub>2</sub> near its boiling point) or in the transition point of hydrogen (2 - 5 K) or oxygen. [13]

The basic design principle should work at relatively high flow rates of cryogenic liquids and gases just as long as the shedding from the delta shaped bluff body is so strong that it varies the direction at which the oncoming flowstreams hit the front face. The major problem which would need to be answered would result from the addition of heat to the flowing media by the self-heating thermistor and the resulting localized boiling and flashing that might probably occur. This would also probably be greatly increased as the flow rates decreased.

Eastech flowmeter design is a relatively new concept, having been commercially available since 1969. Their experience in cryogenics involves only the use of LN<sub>2</sub> in the commercial market. They have no cryogenic calibration facility and no experience in measuring cryogenic liquid or gaseous hydrogen or oxygen. For any future use on a space vehicle, extensive redesign and testing would be necessary; however, the general design concept is sufficiently promising to warrant further evaluation.



The primary advantages of this type of flowmeter are small overall manufacturing and installation costs, virtually no maintenance, and an all digital output. In addition, the ratio of frequency to flowrate (calibration factor) is governed by only two dimensions: the width across the bluff body's face and the inside diameter of the tube, much in the same way that an orifice plate's coefficient is determined by its beta ratio. The advantage this brings to the vortex shedding meter is that all flowmeters of a given size can be built with the same calibration factor, simply by keeping these two dimensions identical on all units. In the case of cryogenic measurements, the additional factor of coefficient of expansion changes would also have to be considered. [13]

#### 3.3.4 Electro Development Corporation

Electro Development Corporation (EDC) manufactures a type four flowmeter using the angular momentum principal. They are primarily an "engineering house" specializing in avionics equipment. Recently they entered the flowmeter field with the fuel flowmeter for the 747, DC-10, F-14, and S-3A airplanes.

They are licensed by Elliotts of England to manufacture their flowmeter design and have integrated it with their electronics to form an angular momentum true mass flowmeter system. Although they have no cryogenic flowmeter design, fabrication or test experience, their flowmeter concept and previous engineering expertise warrants evaluation.

The flowmeter operates on the angular momentum principle and generates two pulse signals which are time displaced an amount proportional to the mass flow rate. These time displaced pulses are used to trigger a high frequency oscillator "on" and "off" to generate a burst of pulses, the quantity of which over a finite time period is proportional to mass flow rate. The high frequency pulses can then be counted or used in a digital to analog converter to provide a display of flow rate.

A cluster of straightening tubes upstream of the orifice plate and pressure taps act as a flow straightener to remove fluid swirl to minimize the effects of upstream piping conditions.

The fluid to be measured is passed through the flowmeter which converts the flow rate into two electrical signals. This is achieved by using the mass of the flowing media to create a proportional angular displacement between two continuously rotating magnets. These magnets, which are driven by a synchronous 100 rpm motor, induce pulses in two stationary coils. The time differences between the pulse induced in coil #1 by magnet #1 and the pulse induced in coil #2 by magnet #2 is a measure of mass flow. This time difference is insensitive to the speed of the motor since slowing down the motor also decreases the angular displacement between the two magnets.

The pulse converter in the electronics unit converts the time between the transmitter pulses #1 and #2 into a rectangular pulse width.

The following is a simplified representation of the flowmeter's basic functions (Figure 3.3.4-1). The low speed motor drive continuously rotates a drum which is spring coupled to an impeller. The impeller contains channels through which media must flow. The larger the media flow rate, the greater the quantity of media to which the impeller must impart angular momentum, and the greater the angular deflection of the coupling spring. Magnets located on both the drum and the impeller indicate the degree of this deflection by generating pulses each time they pass near stationary pickoff coils. The time between the occurrence of the impeller pulse is used as a measure of media flow rate.

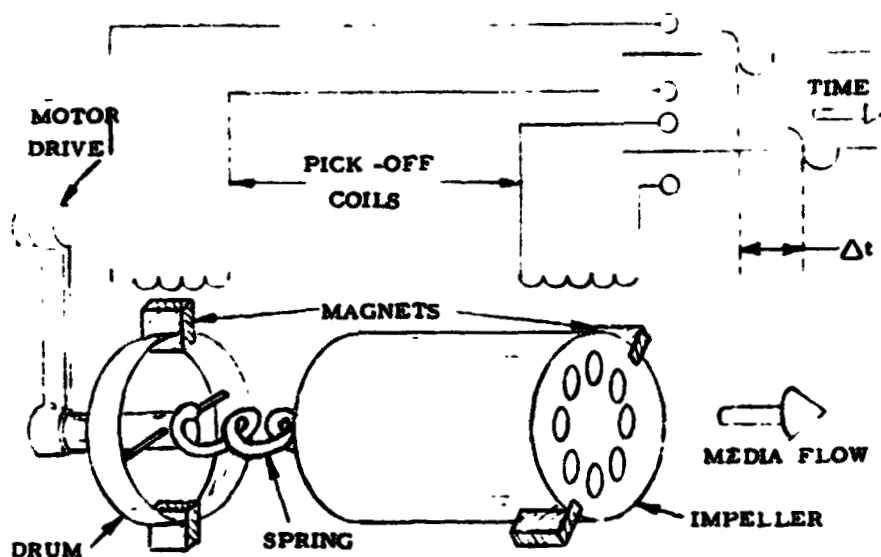


Figure 3.3.4-1 [4] Mass Momentum Meter Assembly

An advantage to this flowmeter design is that it can be used mounted external to the line with only an orifice acting as any obstruction. Figure 3.3.4-2 shows the mass flowmeter mounted external to a 4 inch diameter main body. The flow of the liquid through the main body is accurately divided by a bypass line into the external flowmeter. The fundamental requirement is that a fixed portion of the main media be diverted into the external flowmeter and that this ratio be constant over the entire flow range. By establishing fixed orifices in both the flowmeter and the main body, this condition can be met with some small variations at the upper and lower flow ranges. The external flowmeter provides for adjustments of linear ratio changes.

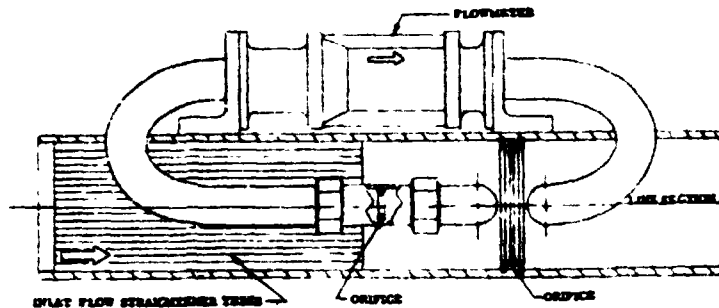
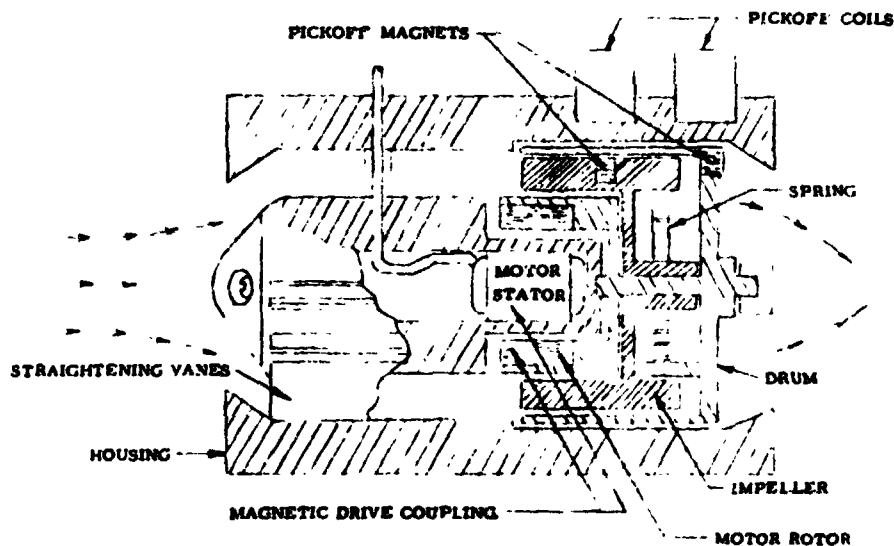


Figure 3.3.4-2 <sup>14</sup> Flow Meter Installation

The size of the main body orifice primarily determines the pressure drop across the main housing. The pressure drop in the main orifice area determines the flow rate through the flowmeter.

Figure 3.3.4-3 shows the operation of the flowmeter. The media entering the flowmeter is first passed axially between radial straightening vanes to remove swirl and other disturbances. The media is then passed through the rotating measurement assembly. This consists of a multi-vane impeller, connected coaxially to a surrounding drum by means of a spiral spring. The drum entirely shrouds the circumference of the impeller thus eliminating any possible viscous drag on the impeller. The drum is rotated at a constant speed synchronous motor unit. The motor housing is supported in the center of the flowmeter by webs, machined integrally with the body of the flowmeter.



MECHANICAL SCHEMATIC: FLOW METER

Figure 3.3.4-3 <sup>63</sup> Mass Meter Cutaway



As a result of the media passing through the annular space in the measurement assembly, the impeller is deflected relative to the drum due to the torque required to impart an angular momentum to the media. Since the spiral spring has a linear torque/deflection characteristic, the deflection angle is therefore a measure of this torque. This assumes a constant angular velocity which is the case in this system since the motor speed is crystal controlled. It follows that the greater the mass flow rate, the larger the deflection measured by attaching small magnets, two each, to drum and impeller circumferences 180 degrees apart and placing two pickoff coils on the outside of the non-magnetic flowmeter body. As each magnet is rotated past its respective pickoff coil, an electrical pulse is produced in the coil. The time displacement of the impeller pulses relative to the drum pulses is thus directly proportional to mass flow rate.

The relationship between mass and time can be seen from the following theoretical analysis:

Let the inner and outer radii of the annular fuel chamber be  $r_1$  and  $r_2$ , respectively,

$n$  = drum angular velocity

$L$  = impeller torque

$\theta$  = angular deflection

$t$  = time between drum and impeller pulses

$\dot{M}$  the mass flow rate

Torque = Force x radius

= mass flow rate x tangential velocity x radius

$$\text{i.e., } L = \dot{M} n \int_{r_1}^{r_2} r dr = \frac{\dot{M} n}{2} (r_2^2 - r_1^2)$$

and since  $n$  and  $r_1$  and  $r_2$  are fixed,

then  $L = k_1 \dot{M} n$  where  $k_1$  is a constant.

If  $k_2$  is the spring constant

then  $k_2 \theta = k_1 \dot{M} n$ .

Now the deflection  $\theta$  is measured by the time ( $t$ ) between electrical pulses.

i.e.,  $\theta = k_3 n t$  where  $k_3$  is a constant

$$k_2 k_3 n t = k_1 \dot{M} n$$

i.e.,  $M \propto t$

The mass fuel flow rate is thus only proportional to the pulse time interval  $t$ . (14)



EDC's previous experience in measuring true mass flow of a hydrocarbon is insufficient to warrant its direct adaption to a cryogenic. If sufficient effort was made on a calibration facility and subsequent cryogenic testing was undertaken this manufacturer has the engineering capability to justify further development effort.

The primary advantage of this type flowmeter is applicable as previously noted to any momentum functionary flowmeter, namely, true mass flowrate. The potential disadvantages other than lack of cryogenic data, either gas or liquid, are: (a) the use of ball bearings in a cryogenic gaseous media, (b) the use of O-ring seals used in the housing, (c) housing material being aluminum, and (d) a possible hydrogen embrittlement problem in the use of a NiSpan spring (42% Ni and 40% iron).

### 3.3.5 Fisher and Porter

This type of flowmeter is of the volumetric turbine type. The turbine rotor is mounted in the path of the fluid stream and is the transducing element of the meter. The fluid stream exerts a force on the blades of the turbine rotor, setting it in motion, thus converting the linear velocity of the process fluid to a precisely equivalent angular velocity producing rotor motion. The rotational speed of the turbine is proportional to the fluid velocity and hence to the volume flow rate of the stream.

The rotational speed of the rotor is monitored by the externally-mounted pick-off assembly. Two types of pickoffs are available on most Fisher and Porter turbine flowmeters, Magnetic and "No Drag" RF. The magnetic pickoff contains a permanent magnet and a coil. As the turbine rotor blades pass through the field produced by the permanent magnet, a shunting action takes place inducing an a-c voltage in the winding of the coil wrapped around the magnet. A sine wave having a frequency proportional to the flowrate is developed. The choice of RF or magnetic pickoff is depending on the rate of flow and the cryogenic temperature. At low speeds, there is a magnetic drag error effect using magnetic turbine blades. In addition, at cryogenic temperatures, some blade material properties change drastically toward less strength. With the "No Drag", RF type pickoff, an oscillator applies a high frequency carrier signal to a coil in the pickoff assembly. The rotor blades pass through the field generated by the coil and modulate the carrier signal by shunting action on the field shape. The carrier signal is modulated at a rate corresponding to the rotor speed, which is proportional to the flow rate. With both pickoffs, the frequency of the pulses generated becomes a measure of the flow rate and the total number of pulses measures total volume.

Since the output frequency of the turbine flowmeter is proportional to flow rate, every pulse from the turbine meter is equivalent to a known volume of fluid that has passed through the meter; totalizing these pulses yields total volumetric flow. Totalization is accomplished by electronic counters specifically designed for use with the turbine flowmeters; they combine a mechanical register with the basic electronic counter. [15]

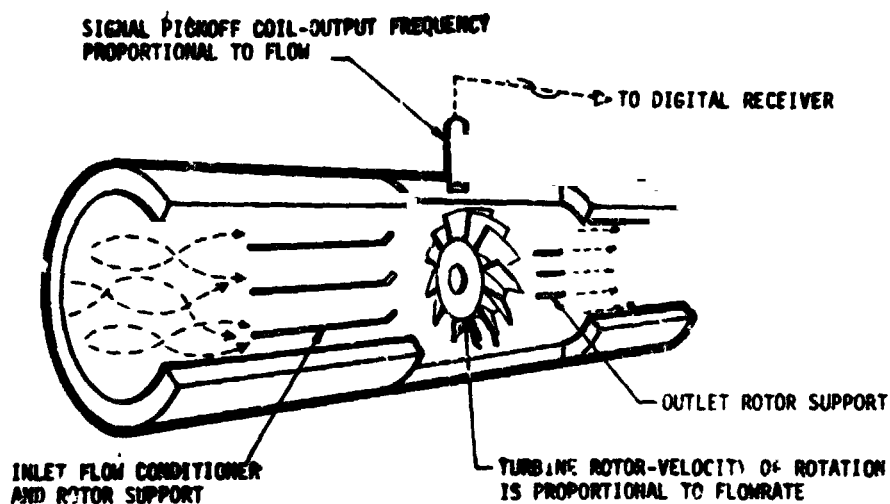


Figure 3.3.5-1 The Fisher And Porter Turbine Meter

This manufacturer does not claim gas flow capability for this turbine meter. In fact, he states the change in state from the liquid (cryogenic) to the gas form means a change in volume, which may be as great as 100 times. [16] The turbine meter senses volume change and this tremendous volume increase represents extreme over-speeding of the rotor, resulting in a short life and probable meter failure.

Fisher and Porter do not provide nor do they recommend any particular type of densitometer. In order to obtain mass flow inferentially, the turbine meter user would have to provide his own density measurement ( $\rho \times V = \dot{M}$ ).

The potentials capability, advantages and disadvantages are the same as the Cox turbinometer. There appears to be little, if any, design difference between the Cox and Fisher and Porter turbinometers.

### 3.3.6 Flow Technology, Inc.

The three types of flowmeters manufactured by Flow Technology, Inc., are of the volumetric flow type. They operate on the principal of the rotating vane and either an RF or magnetic pickoff (Type 1). In the latter, the poor strength characteristics of magnetic material in cryogenics is overcome by inserting magnetic material slugs in the stainless steel turbine blades. The drag error

is still present at low speed but the unit has structural strength. The standard turbine is the primary design and differs little from previously discussed designs. There is only one flow straightener and it is located upstream of the turbine blade. [17]

No densitometer is provided so to determine mass flow inferentially; such a measurement would be needed. The basic design is very similar to the Cox and R&P turbine meters previously discussed and the advantages, potential and disadvantages are about the same. The manufacturer claims capability in measuring liquids and gases but no data have been located to substantiate this. As with each of the 15 flowmeter candidates, further investigation of this type of flowmeter design is warranted because of their past proven experience in measuring volumetric flow of liquid cryogenics.

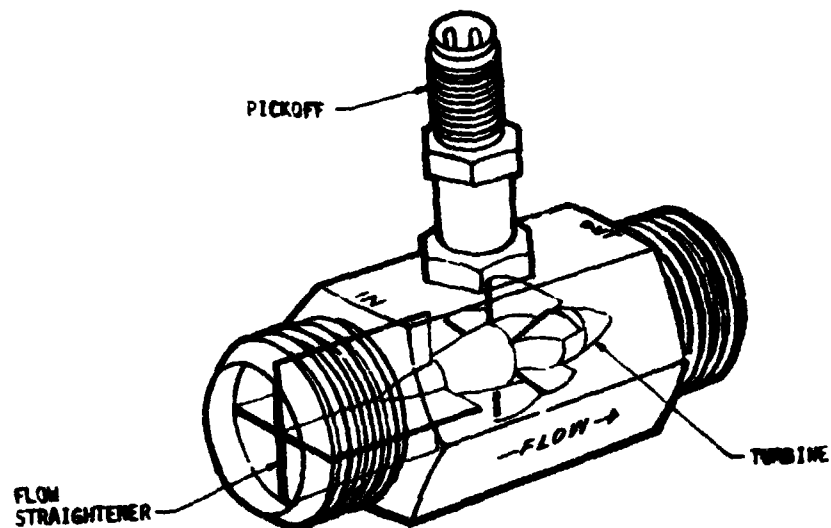


Figure 3.3.6-1 The Flow Technology Turbine Meter

### 3.3.7 Foxboro Instrumentation

Two types of flowmeters are manufactured by Foxboro, a turbine meter [18] and a mass reaction momentum type. The turbine meter is rated for -150 F maximum, uses sleeve bearings and probably would not function in a cryogenic gaseous environment. It is only mentioned to indicate Foxboro's capability.

A mass reaction flowmeter is a true liquid cryogenic mass flowmeter which can be used with liquid oxygen, nitrogen, and argon. Although the Foxboro literature did not reference use with liquid hydrogen, other published data did present calibration information on this meter in  $LH_2$  [19]. The Foxboro literature did reference two phase operation capability but provided no specific test data [20].

The mass metering system is comprised of two components, the flow transmitter (flowmeter) and a converter/totalizer. The flow transmitter is a true mass flowmeter of the momentum type, with a frequency output inversely proportional to mass flow. The converter/totalizer is a solid-state device which converts transmitter frequency to mass flow registration.

The transmitter consists of a straight bladed rotor magnetically coupled to an ac induction motor, and a magnetic pickup coil. The magnetic coupling transfers a constant torque from the motor to the rotor. In the absence of process fluid, the rotor turns at motor speed (Figure 3.3.7-1).

During operation, the process fluid slows the rotor speed according to the following relationship:

$$f = \frac{k}{\dot{M}}$$

$$\text{or } \dot{M} = \frac{(1)}{f}$$

$f$  = rotor frequency or speed  
 $k$  = a meter constant  
 $\dot{M}$  = the mass flow rate through the transmitter, pounds per second

The pickup coil monitors rotor rotation and produces an electrical signal with a frequency which is proportional to rotor speed.

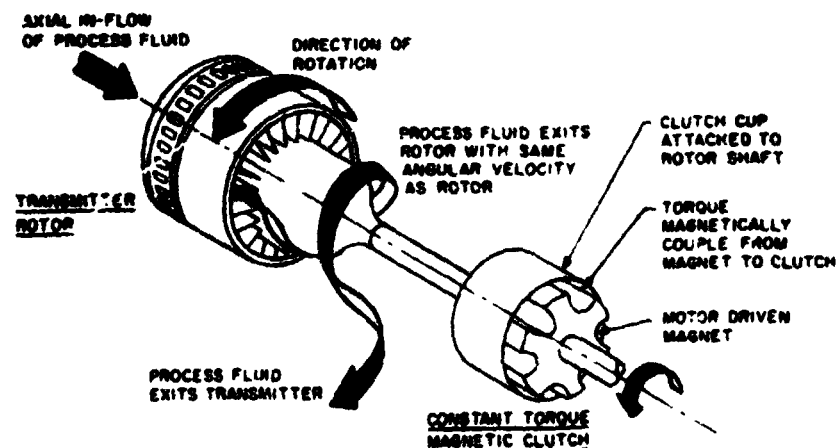


Figure 3.3.7-1 ~~20~~ The Foxboro Mass Momentum Meter



The converter/totalizer uses period measurement to convert the flowmeter signal to mass registration. This is made possible by utilizing the inverse relationship between frequency and period.

$$T = \frac{1}{f}$$

T = flowmeter signal period  
f = flowmeter signal frequency

Substituting this relationship into equation 1b provides a direct relationship between mass flow and flowmeter signal period

$$\dot{M} = k \frac{(1)}{T} = k T$$

Circuit logic is designed to measure the transmitter period (T), multiply by the transmitter constant (k), and produce a driving signal for counter operation.

This meter has been used a great deal in the cryogenic liquid transfer field. The meter is position-sensitive and designed for only vertical (+10 degrees) use; therefore, its use on airborne equipment is questionable. In addition, there are no data available on its use as a true mass gas flowmeter. The drive motor is mounted exterior to the flowing cryogenic and in conjunction with a hysteresis drive is connected to a single axial vaned impeller (Figure 3.3.7-2).

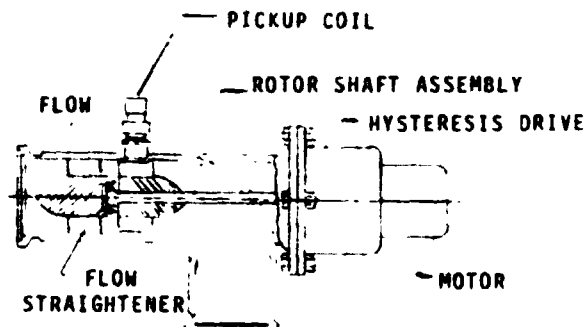


Figure 3.3.7-2<sup>(2)</sup> The Foxboro Mass Meter Installation

Torque is maintained constant and the impeller speed is varied inversely with the mass flow rate. A measure of the impeller speed is a measure of the mass flow rate. This scheme has the characteristics of high resolution at low flow rates and decreasing resolution as the flow rate increases. The basic angular true mass design warrants further investigation for use as a true mass cryogenic gas flowmeter.

### 3.3.8 General Electric Company

The flow measurement system developed by General Electric is an angular momentum design (type four) flowmeter. It consists of a flowmeter transmitter, an indicator, an electrical power source, and associated cabling and plumbing. The flowmeter transmitter is comprised of two components -- a primary detector and a bypass element.

The primary detector senses angular-momentum rate, which is dependent upon mass rate of flow. Its function is to generate an electrical voltage signal proportional to the true mass rate of fluid flow. The bypass is a conventional orifice plate in a main pipeline. The purpose of the bypass is to divert a fixed fraction of total flow from the sensor.

The flow sensor comprises seven basic elements -- two rotors, a restraining spring, an electromechanical pickoff, a drive mechanism, a flow chamber, and a housing for the electrical components.

The primary hydraulic elements are two similar axial flow rotors disposed end-to-end within the fluid chamber (Figure 3.3.8-1).

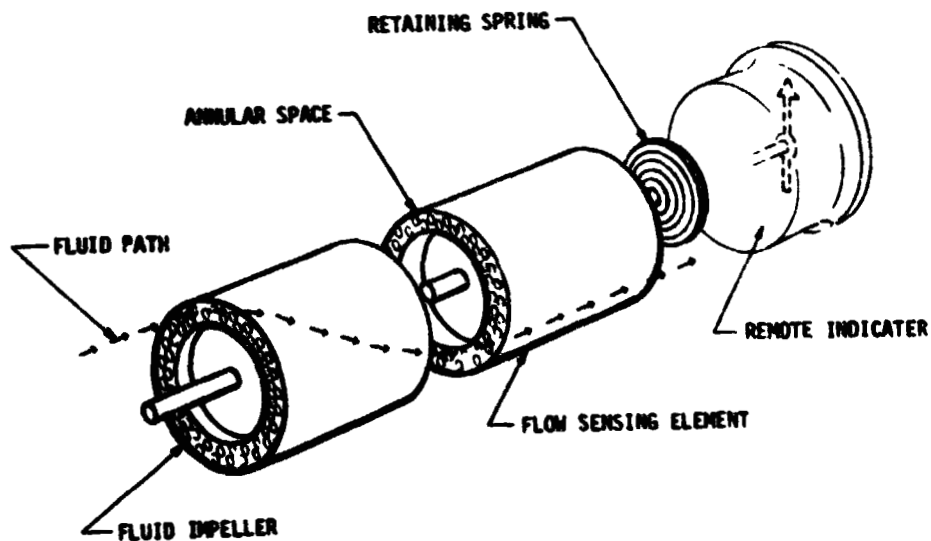


Figure 3.3.8-1 The General Electric Mass Flow Meter



The upstream rotor is an impeller that imparts constant angular momentum to each unit mass of fluid in transit. The downstream rotor is a spring-restrained element that removes all angular momentum from the fluid. In consequence of Newton's third law, the fluid exerts a mechanical torque that is in precise linear proportion to mass flow rate, independent of density, viscosity, or any other physical property of the fluid or environmental condition. The downstream rotor is restrained by the spring to deflect proportional to torque. The pickoff operating in conjunction with the downstream rotor generates an ac voltage proportional to deflection.

The fundamental equation relating the transmitter output signal to the flow is as follows:

$$V = k_B M R^2 \omega k_v / k_s$$

where  $V$  is the transmitter output voltage signal,  $k_B$  is the ratio of flow through the sensor to the total flow,  $M$  is the total mass rate of flow,  $R$  is the impeller flow passage radius of gyration,  $\omega$  is the impeller angular velocity,  $k_v$  is the pickoff voltage gradient, and  $k_s$  is the turbine restraining-spring constant. The equation is general and holds for any consistent unit system. It is a direct statement of Newton's law under steady-state conditions, incorporating necessary physical constants of the components contributing to the measurement.

The function of the bypass element is the same in principle as that of a shunt resistor in parallel with a millivoltmeter in the measurement of electric current. The basic operational requirement is that the division of flow between sensor and bypass be in constant ratio. Hydraulic design must be such that the flow rate to pressure drop ratio of the bypass element and that of the flow sensor are equal over the operating range. This condition obviously would be met if both elements followed precisely the square law of pressure drop versus Reynolds number. Both elements deviate slightly from the square law, but they deviate by equal amounts. Consequently, the division of flow is constant to a high degree of precision over the entire operating range.

An important design factor is maintaining turbulent flow conditions in the sensor and bypass over the operating range. Otherwise a precisely constant division of flow would be difficult to maintain over the transition region. Fluid turbulence prevails in the sensor fluid chamber at all flow rates, even zero, by virtue of continuous impeller motion. Over any practical flow range, turbulence in the bypass can be maintained through proper selection of pipe and orifice dimensions.

Additional latitude of bypass dimensional control may be obtained by introducing a second orifice in the flow sensor piping. The flowmeter is designed to incorporate the second orifice, although test data indicate that it is not a functional requirement where only a small fraction of total flow passes through the sensor.

In hydraulic and mechanical design, the bypass element is a simple, rugged, and highly reliable structure. It carries a large fraction of total flow, thereby relieving the flow sensor of a substantial burden. This permits standardizing the flow sensor design for use with flowmeters covering a wide range of flow capacities and fluid properties. The range in flow capacities, without modifying the sensor or sacrificing performance characteristics, can be as low as one lb/sec full scale, and there is no upper limit. Except for possible secondary effects on pressure drop, there are no limitations on the diameter of the main pipeline. Different flow capacities and pipe diameters are accommodated through orifice design. Extreme versatility, reduced size, weight, and cost, and high reliability are significant advantages realized through use of a bypass element in conjunction with this mass rate-of-flow sensor.

Particularly close attention is given to mechanical and hydraulic design of the sensor to obtain optimum performance. Spurious vortices and cavitation are inhibited through flow passage contours having no abrupt changes in direction or area. Secondary effects on linearity due to flow passage irregularities and fluid coupling phenomena are suppressed by means of balance of impeller speed and axial fluid velocity and through flow passage geometry (Figure 3.3.8-2). By subdividing the impeller flow passage with a multiplicity of thin-walled tubes, the effects of fluid coupling are made negligible. Rotor axial misalignments are minimized by mounting both rotors on a common shaft through precision ball bearings.

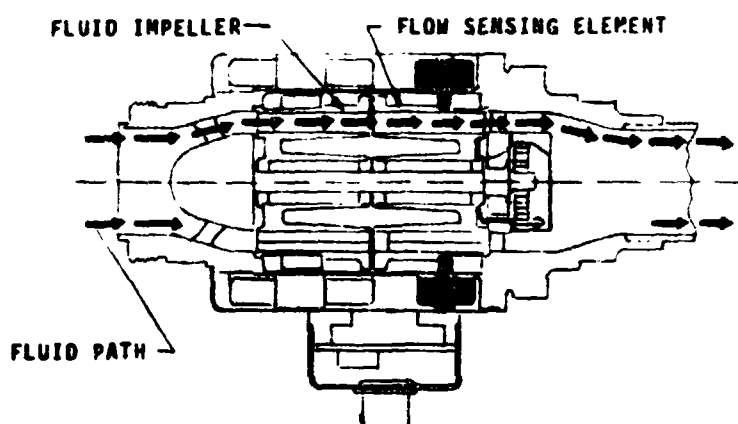


Figure 3.3.8-2 **20** Cutaway View of the Mass Meter



The sensor output signal is generated by a brushless position-to-voltage transducer. Operation is equivalent in principle to the well-known differential transformer. The pickoff element in the fluid consists of two symmetrical segments of a laminated hollow, soft iron cylinder rigidly mounted on the downstream rotor. The stator, radially symmetrical and concentric with the downstream rotor, comprises four salient poles of laminated soft iron and a magnetic flux return path. It also carries all coils associated with the pickoff. Although the rotor is exposed, the stator is located external to the fluid flow, separated from it by the flowmeter casing.

The upstream rotor, or impeller, is driven at a relatively low, precision-controlled constant speed (240 rpm) by a two-phase synchronous motor. The entire mechanism includes a cylindrical permanent magnet rotor that is an integral part of the impeller and a stator mounted outside the fluid chamber. Electromechanical functions of the flow sensor fall in two categories -- maintenance of constant impeller speed and detection of angular deflection of the pickoff rotor. The motor drive and pickoff signal power are transmitted by magnetic fields through walls of the fluid chamber.

The use of this type of flowmeter in gaseous service on a continuous basis is subject to further study and specific detailed testing. Erosion due to prolonged exposure and ball bearing failure are two problems not fully understood. The use of O-rings or silver-plated inconel chevron rings and hermetic seals such as inert welds are a subject of further study if this design is to be fully developed. Test data have been accumulated during two phase flow and although accuracy decreased, the flowmeter continued to function. This information was obtained over a short time span and considerable additional testing would be necessary to validate the design for continued gaseous cryogenic flow.

### 3.3.9 Hastings - Raydist

The Hastings-Raydist mass flowmeter is an example of a type five thermal flowmeter. It is predicated on the principal that mass flow can be inferred from the change in temperatures of a stream subject to a known heat flux. Several techniques can be employed, one of which consists of an electrically heated tube and an arrangement of thermocouples to measure the differential coating caused by a fluid passing through the tube. Thermoelectric elements generate dc voltage proportional to the rate of mass flow through the tube.

In the heated tube system fluid passes through a tube, uniformly heated by a transformer. The temperature distribution about the mid-point is symmetrical at zero flow, so that thermocouples TC-1 and TC-2 cause a null readout (Figure 3.3.9-1).

Fluid passes through the tube, and temperature distribution becomes asymmetrical. For a constant power input the differential thermocouple output indicated on the meter is a function of heat capacity and the mass flow through the tube.

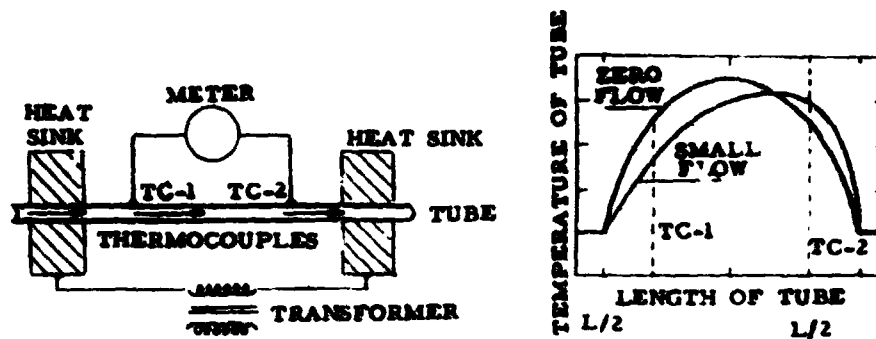


Figure 3.3.9-1 (2) Mass Flow Meter Schematic And Flow Relationship

The relation between the rate of flow of fluid and the heat input is expressed by the following equation: [23]

$$H_t = \dot{M} C_p [(TC-2) - (TC-1)]$$

or

$$\dot{M} = \frac{H_t}{C_p [(T-2) - (T-1)]}$$

where  $C_p$  = specific heat of the fluid at constant pressure, BTU/lb/F

$H_t$  = heat energy supplied by the heater, BTU/sec

$T_1$  &  $T_2$  = entrance and exit temp respectively, F

$\dot{M}$  = mass flow rate of the fluid in lb<sub>m</sub>/sec

Theoretically, this general type of thermal flowmeter should be able to measure liquid as well as gas flow. In application, gas has been the measured media flowing. No data have been found where this particular manufacturer's flowmeter has been used to measure mass gas flow at a temperature less than 0 F. Errors due to ambient temperature changes and pressure fluctuations can be as great as 2 to 3% over a 120 F temperature and 250 to 1500 psig pressure range.

Although no cryogenic gas data are available, it can be assumed that the basic heat transfer principal is applicable to this particular meter. Establishing the validity of this statement would require extensive testing using several cryogenic gases at a variety of temperatures ranging from just above the liquid boiling point to zero degrees.

The major advantage of a thermal type mass flowmeter is that its output is in mass directly. Its disadvantage is the lack of data in a cryogenic gas application. The potential capability is sufficient to warrant further investigation and certainly calibration using a gaseous media such as nitrogen at or near -300 F.

### 3.3.10 Honeywell, Inc.

The Honeywell mass flowmeter uses an oscillating drag body in a second order, linear, spring mass system. The system damping is supplied by the mass flow rate of the fluid, and the reaction between the fluid and drag body is electronically monitored to accurately measure mass flow rate. Figure 3.3.10-1 illustrates a simplified model of the sensor.

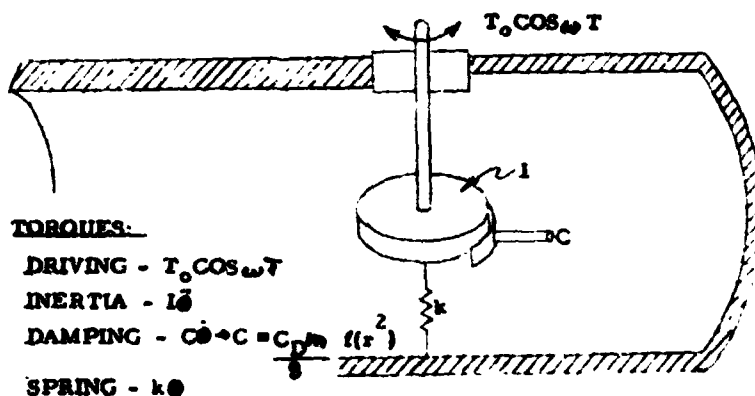


Figure 3.3.10-1 [24] Mass Meter Schematic

The meter consists of a drag body, torsional spring, torquer, rate sensor, and signal conditioning electronics. The drag body is placed in the flow stream and is electronically forced into torsional oscillation. This oscillation is damped by the flow and the amount of damping is linear with mass flow rate, so that damping is the parameter measured. The torsional spring serves to determine the frequency of oscillation and also serves as the drag body support so that bearings are not needed. The torquer is used to force the oscillation. The rate sensor senses the oscillation. The signal conditioning electronics, drag body, torquer, and rate sensor thus form an electromechanical oscillator. The signal conditioning electronics utilize an automatic gain control (AGC) technique to maintain sinusoidal oscillation and to determine damping. [25] (Figure 3.3.10-2).

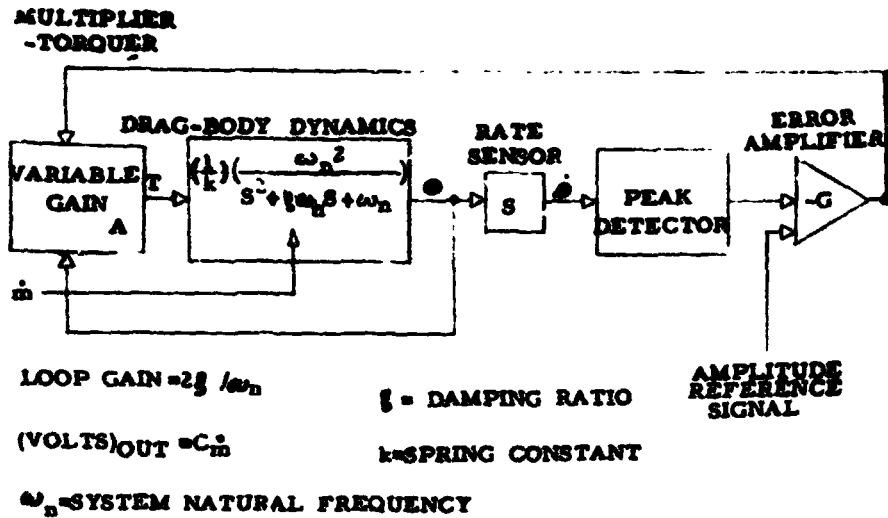


Figure 3.3.10-2 <sup>(20)</sup> Mass Meter System Diagram

Consider a drag body about 5/8 of an inch in diameter placed perpendicular to the flow stream and suspended about the axis of rotation. The mode of operation is to rotate the drag body about this axis of rotation in an oscillatory manner as described in the following equation:

$$\theta = \theta_0 \cos \omega t \quad (1)$$

To describe the effect of the fluid on this motion, it is assumed that the axis of rotation divides the drag body into two sections, each of which acts as an independent body. The well known drag force law of Equation (2) is applied to each half.

$$F_D = \frac{A C_D \rho V^2}{2} \quad (2)$$

Due to the forced rotation the velocity of each half of the plate relative to the fluid will be different, videlicet, one will be  $V + r\dot{\theta}$  and the other will be  $V - r\dot{\theta}$ . If  $V$  is always greater than  $r\dot{\theta}$  the torque acting on the drag body is given the following equation:

$$T = r(F_1 - F_2) \quad (3)$$

$$= \frac{r A C_D \rho}{2} [(V + r\dot{\theta})^2 - (V - r\dot{\theta})^2] \quad (4)$$

Expanding the terms in Equation (4) and simplifying, results in the following expression for the damping torque:

$$T = 2r^2 C_D A \rho V \dot{\theta} \quad (5)$$

The mass flow rate is defined by,

$$\dot{m} = A_p \rho V \quad (6)$$

so that the damping torque can be written as,

$$T_D = kr^2 C_D \dot{m} \theta \quad (7)$$

Since  $r^2$  and  $C_D$  are parameters of the drag body and must be kept constant for proper meter operation the torque equation can be further simplified

$$(C = r^2 C_D) \quad T_D = kC\dot{m}\theta \quad (8)$$

Equation (6) illustrates the fundamental relationship between the damping torque and mass flow rate. This equation is used below to establish the characteristic equations that describe the flowmeter.

To completely characterize the flowmeter, a spring torque and system inertia must be considered. The inertia adds a term  $I\ddot{\theta}$  (the torque motor inertia is added to the drag body inertia). Since the drag body is restrained by a torsional spring so as to be perpendicular to the flow stream, a torque term of  $k\theta$  is also added. The differential equation which describes the system can thus be written:

$$I\ddot{\theta} + (kC\dot{m})\dot{\theta} + k\theta = T_0 \cos \omega t \quad (9)$$

Equation (9) is a classical second order, linear equation and can be written in Laplace Notation as,

$$\frac{\theta}{T} = \frac{1}{k} \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (10)$$

where

$$\omega_n = \sqrt{k/I}$$

$$\zeta = kCm/\sqrt{kI}$$

The flowmeter is thus equivalently described by the differential Equation (9) where the flow rate is proportional to the damping term or by the transfer function (10) where the flow rate is proportional to damping ratio. [26]

The basic design of the linear momentum flowmeter requires no bearings or rotating members. Also, no slip rings or wear surfaces are present. Oscillations are restricted to less than 1 degree by the torque motor and torsional spring.



The torque motor is an inductive device with both torque and position windings on the same stack. Thus it provides input torque to the system and reads the output at the same time.

The torsional spring is a quadrelve developed for gyroscope applications. It is linear and temperature stable as well as rigid when subjected to side loads.

The primary advantage of this design type is that it measures mass rate directly and therefore eliminates the buildup in errors and complex circuitry requirements of an inferential flowmeter.

Principal disadvantages are a Reynolds number limitation of greater than 11,000, a rather large power consumption of 35 watts under maximum flow and a null shift of 40 mv from air to  $LN_2$  at one atmosphere. In addition, the present concept is incompatible with oxidizers and a flow noise problem requires further study. [25]

The present cryogenic data available are insufficient to really establish the flowmeter capability for cryogenic use, and no data are available on two-phase or gaseous mass flow measurement. The present design will in all probability not function in gaseous flow at low rates. The design is unique enough to warrant further study.

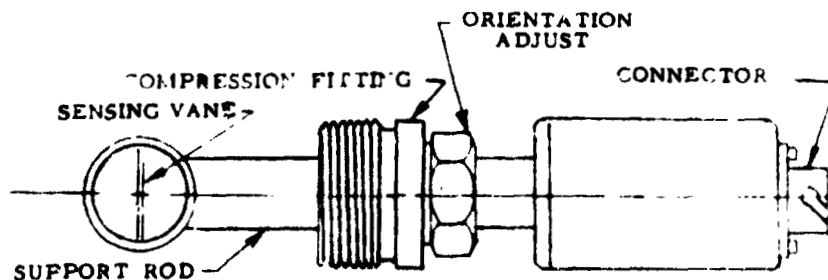
The facilities at the Honeywell Aerospace Division are quite complete and although they do not have a cryogenic test setup, they do have a flow bench using hydrocarbon fuels. The Honeywell corporate resources are in support of this project, and it will undoubtedly be available in the non-cryogenic military and commercial market in the near future. [27]

### 3.3.11 ITT Barton

The Barton turbine flowmeter design is a type one flowmeter and consists of a rotating vane and magnetic pickoff. The flowmeter design group is comprised mainly of former "Pottexmeter" personnel and represents over twenty years of flowmeter design and manufacturing capability. [28]

In this design the rotor is suspended on a sleeve-type tungsten carbide bearing between two flow straighteners which consist of three bodies of equal diameter. The pickoff coils fall into two basic categories; reluctance and inductive. The reluctance or active coil consists of a magnet and coil of wire placed in proximity to the rotor blades of the turbine meter. The inductive passive pickoff coil is similar to the reluctance coil except in this case it is the magnet that actually moves and produces the variation of the magnetic field. The inductive coil is employed when the corrosive characteristics of the fluid (liquid or gas) are such that the magnetic series of stainless steel cannot be used. A corrosive resistant material is used and a magnet is encapsulated within the rotor generating a signal within the external inductive pickoff coil as the rotor turns. As noted above, a sleeve bearing is used between the shaft and rotor. This bearing sees little or no thrust due to flow and is actually in a null position relative to downstream thrust. A series of holes in the hub sets up a differential pressure across the bearing which induces a counter current flow equal and opposite to flow. The rotor consists of a hub into which are inserted blades. The number of blades and the measured flowrate establish the resolution of output. The rotor sits on a shaft with the flow straighteners and the upstream and downstream diffuser on either side.

A separate vibration-type densitometer is used in combination with the volumetric flowmeter to give an output in mass flow. [29] The densitometer is made up of a thin vane symmetrically positioned within a thin-walled cylindrical support. The vane is driven at its natural frequency by means of a remotely located driver and detector, causing the fluid surrounding it to be accelerated by its motion. The reaction of the fluid mass causes the vane to oscillate at a frequency which is a function of fluid density. Therefore, density ( $\rho$ ) times velocity ( $V$ ) is equal to mass rate of flow ( $M$ ).



[29]  
Figure 3.3.11-1 ITT Barton Densitometer

This type densitometer may be used in either static or dynamic applications, and such factors as fluid flow, pressure, temperature and viscosity have virtually no effect on its measurement precision. Because of their mechanical and electronic simplicity, vibration-type densitometers are well suited for many density measuring applications, including those of flowing fluids. Their small size and weight, accuracy, sensitivity, and fast response are significant positive features. Vibration-type densitometers can be used in both dynamic and static fluid applications. Further, they can be used in any position, on earth or in deep space, pip lines, tanks or other vessels. It offers minimum obstruction to flow and transfers a minimum amount of energy to the liquid.

The equation ( $\rho = \frac{A}{f^2} + B$ ) describes the basic function of all vibration-type densitometers. This relationship can be exploited in a practical measuring device by providing a means of maintaining a oscillating plate at its resonance frequency as required.

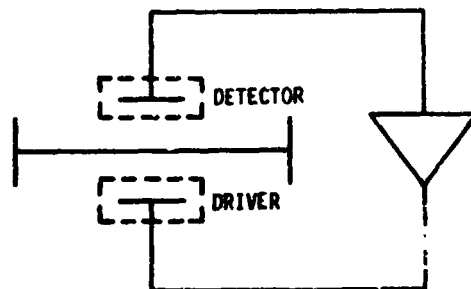


Figure 3.3.11-2 [29] ITT Barton Densitometer Detector Schematic

A detector is positioned such that it senses the mechanical displacement of the plate and produces an electrical signal which is proportional to the displacement. This signal is then amplified and furnished to the driver which, in turn, imparts a mechanical driving force to the plate equivalent in frequency to the detector signal. Since the plate will experience the largest displacement when it is driven at its resonant frequency. By means of a "closed loop positive feedback" technique, an electrical signal is produced whose frequency is equivalent to the mechanical resonance of the plate. A measure of this frequency provides a measure of fluid density.

ITT Barton has two additional advantages over others mentioned; the null thrust bearing and the use and experience of manufacturing their own densitometer.



The disadvantage of excessive bearing wear appears to be negligible due to the previously mentioned patented design which sets up a differential pressure across the bearings. The need for a densitometer reading is still somewhat of a disadvantage but since ITT Barton has the design experience of such a meter, the impact is not as great as those flowmeter manufacturers that do not have this capability.

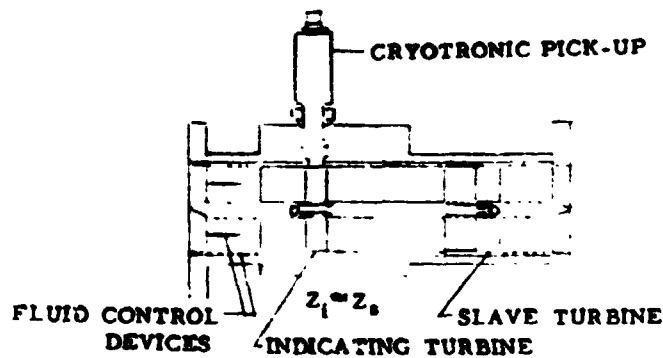
Flowmeter calibration equipment using water is available at three test stands. The total flowmeter facility is approximately 20,000 square feet. No cryogenic facilities are available for either liquid or gaseous hydrogen or oxygen. As noted before, little or no cryogenic test data for a liquid using this meter is available and none is available for mass gas cryogenic flowrates.

### 3.3.12 Quantum Dynamics, Inc.

This is a small laboratory type flowmeter company which manufactures a turbine type vane impeller utilizing an RF type pickoff. The velocity of the fluid rotates the vane which interrupts the RF signal, the resulting pulsed output is proportional to flow. Several unique characteristics of this design are the use of a dual turbine setup which allows relatively no bearing movement or load under flow and the use of an integral capacitance measurement to give an output of density proportional to dielectric constant.

The President of Quantum Dynamics (Q.D.) is Dr. Fredrick Liu who has published a number of international papers and is considered an authority on various phases of cryogenic flow phenomena. The Q.D. facilities are fairly small, consisting of primarily a test lab, machine shop and an electronics design assembly area.<sup>(30)</sup> Although small, the facility capability in design and fabrication seems to be more than adequate in regards to the flowmeter design and the electronics associated. Calibration facilities are available to establish the flowmeter characteristics either using the actual media or approximating it.

As previously noted, Q.D. flowmeter design utilizes several unique principles. Two sets of rotating blades, mounted to a single shaft, result in a near flow impedance match. An "indicating" turbine rides "piggie back" on the rotating shaft of a slave turbine.<sup>(31)</sup> Both turbines respond to the same flow at approximately the same speed so the relative motion between the indicating turbine and its bearing shaft is maintained at near zero level. A near zero impedance zone between the two turbines is created. This then reduces the retarding force to a constant minimum level over an extremely wide range of flowrate. Besides long bearing life, this results in exceptional response sensitivity and two well matched impedance zones in the flow field — a feature which is highly beneficial from the fluid-dynamics standpoint. (Figure 3.3.12-1) The sensing pickup does not operate on the principle of magnetic frequency pickup and as such, does not suffer from the resultant magnetic drag errors. It instead operates at megahertz frequencies which imparts no retarding force to the movement of the turbine. This pickup uses a servo-controlled electromagnetic wave absorption principle. Free from temperature dependent magnetic coupling, the cryogenic pickup can be used as effectively at temperatures of 10K as at 300K.



[31]  
Figure 3.3.12-1 Quantum Dynamics Turbine Meter Cutaway

By adding a density measuring device to the flowmeter, a mass flow system can be produced. The measurement of dielectric properties of the media is converted to a direct indication of density. The density measurement section, hereafter referred to as the dielectric-to-density converter (DDC) is based on the sensing of the dielectric constant of the fluid, but the measured density ( $\rho$ ) is obtained by on-line electronic computation of the Clausius-Mossotti ratio  $(\epsilon - 1)/(\epsilon + 2)$  which is shown by the Lorents macroscopic dielectric theory, and subsequently by the Debye equation, to be a linear function of density. [31] The present DDC is a concentric cylinder with shield ring design. Its dielectric measurement circuit operates at radio-frequency and generates a 0 to 5 volts analog electronic output which is directly proportional to the fluid density (Figure 3.3.12-2).

The DDC used in mass flow measurement essentially measures the average density integrated over a designed length of fluid column. The dimensions of the cylindrical capacitors thus determine the dynamic response of density sensing. However, for local sensing the electronic response of DDC can be made extremely fast.

The dielectric sensing device is fabricated as a series of rings and can be an integral part of the flowmeter. The totalized system output may be in either mass flow, volumetric flow or both.

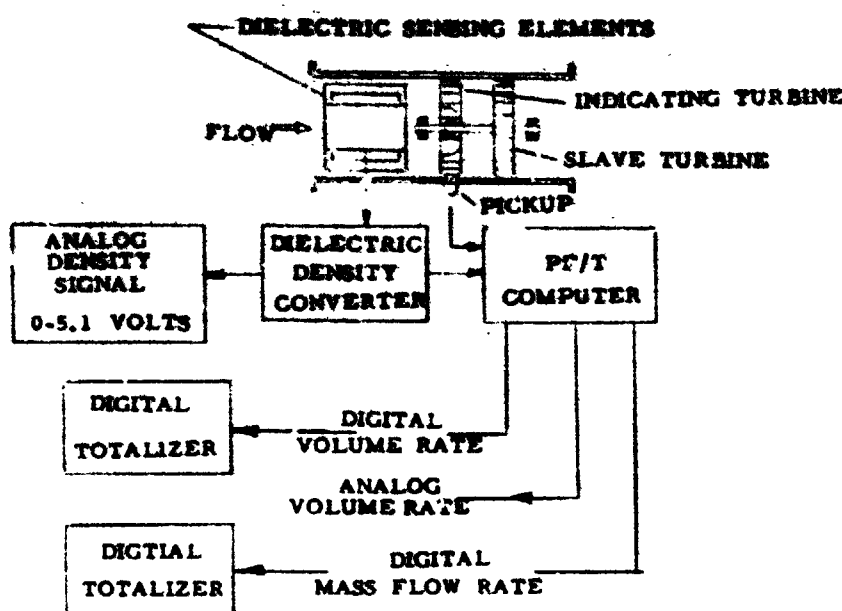


Figure 3.3.12-2<sup>[19]</sup> Quantum Dynamics Inferential Mass System

Quantum Dynamics' primary advantage is their approach to the design and manufacture of a mass flow measuring system. Material selection and fabrication excellence is backed up by careful theoretical calculation and finally empirical testing is done to verify the basic design. The concept of using a turbine meter and a capacitance densitometer to determine mass flow inferentially is not new. Two other manufacturers use the same approach. The implementation of the concept is most unique, however. The turbine-meter bearing design, which is based on the Petroff-Sommerfeld theories [31] eliminates the prime problem of bearing damage due to high gas velocities which has been a major problem of the turbine meter design. Quantum Dynamics' data accumulated on the transition phase of LH<sub>2</sub> from a liquid to a gas (20-23K) [32] is the only information to be found on this subject. The disadvantage of Q.D.'s system is that it does not measure mass flow directly but inferentially and therefore requires a complex measuring system.

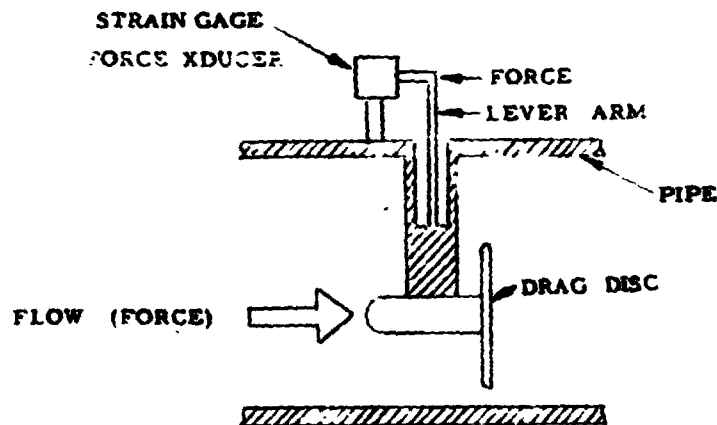
### 3.3.13 Ramapo Instrument Co.

The Ramapo Instrument flowmeter is of the fixed area or drag/target/design (type two). The moment of the following fluid against the target deflects a cantilevered beam to which is attached one leg of a balance strain gage bridge. The construction is simple with no moving parts necessary and the results are a simple rugged flowmeter. (Figure 3.3.13-1) The output is proportional to strain and equivalent to  $\rho v^2$ .

$$\text{Force} = C_D A \rho \frac{v^2}{2g} \quad \text{wherein}$$

$C_D$  the drag coefficient is a constant depending on the configuration of the drag body, the beta ratio and the lines' Reynolds number. The area  $A$  and  $g$  are known constants. [33]

To extract mass flow from this type of flowmeter, an inferential method must be used. Since the output signal of the flowmeter is  $\rho v^2$ , it can be made to yield mass flow by making an independent measurement of fluid density ( $M$ ), performing the division  $\rho v^2 / \rho = v^2$ , extracting the square-root of  $v^2$  to give  $v$ , and finally multiplying  $\rho$  by  $v$  to yield mass flow ( $M$ ). This requires a somewhat more complex electronic integration of both the densitometer and flowmeter signals.



[34]  
Figure 3.3.13-1 Ramapo Drag Body Volumetric Meter



Ramapo does not possess this density measuring capability and only manufactures and provides the flowmeter.

No information is provided by the manufacturer as to his cryogenic calibration capability.

The advantages of this type of drag body design flowmeter are simple construction and no moving parts. The primary disadvantages are typical bonded strain gage temperature errors, a lack of cryogen data and the necessity for a density measurement in order to obtain mass flow.

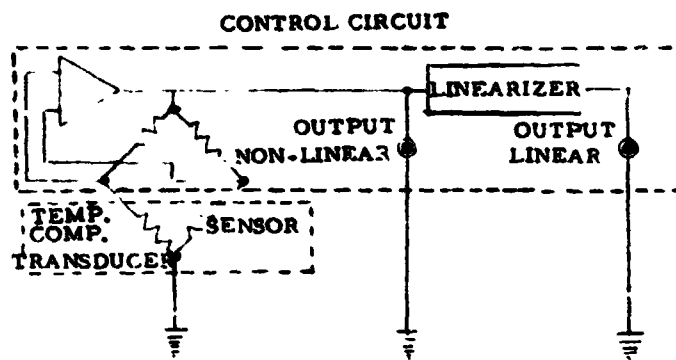
#### 3.3.14 Rosemount Engineering Co.

Rosemount does not at present manufacture a mass gas flowmeter, however, since they represent the only thermal type flowmeter actually used in a practical application, they are presented for their historical information. [35]

During 1964, North American Rockwell established requirements to measure low rates of mass flow of  $H_2$  and  $O_2$ . Ambient temperatures of  $-65^\circ F$  were expected and the low gas temperatures were  $-125^\circ F$  and  $-175^\circ F$  for the  $O_2$  and  $H_2$  respectively. Each transducer shipped from Rosemount went through a complete calibration at the above noted limits prior to delivery. All hardware performed within tolerance ( $\pm 5\%$ ) while mounted and used in the rather limited test location [36]. Subsequent test at NP after qualification was to uncover certain inherent design deficiencies. The transducer which included the electronics and the thermal flow gage, was attitude sensitive, pressure change sensitive, media, vibration and shock sensitive, non-linear in output and thermal heat transfer sensitive between the case and the mounting surfaces. Most of the above problems could have been resolved with some basic redesign of the unit. As it finally turned out that the sensor in use actually saw a much more mild environment and was located on a horizontal plane between two fittings, no redesign became necessary. The final measurement configuration performed well within the final accuracy requirements of  $1\%$ . [37]

Rosemount's design of a mass flow sensor consists of two identical self-heated resistance elements (refer to Figure 3.3.14-1). These elements differ only in that one element (A) is allowed to transfer heat to the flow medium while the other element (B) is not. The transfer of heat from element A is a function of the thermal mass flow rate ( $C_p \rho V$ ) of the medium being measured. Where  $C_p$  is the specific heat,  $\rho$  is the density and  $V$  is the volume flow rate. The temperature (and resistance) of element B is not influenced by the thermal mass rate and is representative of the no-flow condition. The identical design of both elements should cancel out any other influence which may affect the output directly, such as the heat conduction through the case of the sensor.

The resistance of both elements are compared in a bridge. The results of this comparison are likewise a function of thermal mass flow rate ( $C_p \rho V$ ).



[40]  
Figure 3.3.16-1 Thermo-systems Thermal Mass Meter Schematic

The temperature compensating element is adjusted to give a constant voltage versus mass flow output from the control circuit even though environment temperature changes. It does this by changing sensor temperature in a manner to account for both changes in temperature differences ( $t_s - t_e$ ) and changes in temperature sensitive fluid properties.

For a given fluid media, the sensor measures local  $\rho V$ . Its position in the center of the nozzle allows an accurate and highly repeatable determination of total mass flow independent of temperature and pressure variations.

Two outputs are provided. One output is the non-linear signal directly from the bridge circuit, while the second output is linear with mass flow.

The flow transducer has a heated platinum film sensor on a support located at the throat of a smooth venturi. A quartz coating over the platinum film provides protection to the sensor. Inlet screens straighten flow and trap large particles. In clean fluids, the screens can be removed for lower pressure drop. The transducer has no moving parts and will withstand high levels of shock and vibration. [40] (Figure 3.3.16-2)



It should be noted in the definition of  $W$  that  $L$ ,  $k$ ,  $P$ ,  $C_p$  and  $A$  are constant for a given fluid and sensor at a given temperature and pressure, hence, the parameter  $W$  is proportional to the mass flow rate.

The principle of operation of the REC Thermal Mass Flow Sensor is based upon laminar flow through the elements, and also dictates that there will be a sensitivity reduction at high flow rates. These factors act to limit the range of the unit at a maximum of about 100,000 scc/min gas flow rate and about 2000 scc/min for liquids. Minimum full scale flow rates are about 5.0 scc/min for gases and about 0.1 scc/min for liquids.

Sizing of the REC Thermal Mass Flowmeter is accomplished by varying the number of shunt tubes within the sensor such that the amount of flow passing through the sensitive element is nearly always the same.

Since the output of the REC Thermal Mass Flow Sensor is a function of the  $C_p \rho V$  of the fluid, if mixtures of various fluids are to be measured, care must be taken to assure that for variable mixtures, the  $C_p$ 's of the constituents are equal. For mixtures of fluids with dissimilar  $C_p$ 's, the resultant mixture  $C_p$  must remain constant within the limits of sensor accuracy requirements.

Variation in  $k$ ,  $P$ , and  $C_p$  with temperature and pressure will cause systematic errors. These errors are corrected by design techniques defined as "compensation". Variations in  $L$  and  $A$  cause negligible error.

Compensations of the effects due to temperature for the thermal conductivity, specific heat at any one pressure and the power change can be achieved using a third element located in the same heat sink and measuring the heat sink temperature. This has been accomplished by using this element to program the voltage to the bridge or the output from the bridge, as a function of the temperature and hence, compensating for the error. This compensation is linear, allowing the compensation network to be set to provide zero error at two flow points in the flow range. Over the rest of the flow range, an error will occur and will be due to the differences in shape between the compensation curve and the actual error curve.

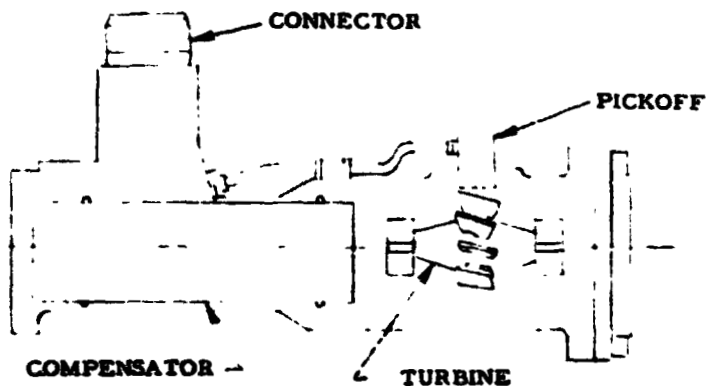
The temperature coefficient of the Thermal Mass Flowmeter (TMF) will be compensated to within 0.025 per °F for most fluids and ambient temperature spans.

The sensor can be designed to operate anywhere within temperature range of -250 F to +500 F providing that no change of state of the measured fluid occurs within that range. For wide temperature range operation, the sensor can be provided with an internal heat exchanger and temperature control circuit to maintain the fluid temperature within a range that will allow good measurement accuracy. (37)

In actual operation, the basic equation and predicted values were not obtained. The sensitivity problems previously mentioned leads to the conclusion that further work is necessary on this design.

### 3.3.15 Simmonds Precision

Simmonds Precision makes a type one inferential mass flowmeter by combining a density and velocity of flow measurement. A rotating vane and magnetic pickoff is used with a capacitance measurement. A honeycomb flow straightener precedes the turbine blade which is upstream of a set of parallel capacitance cylinders. The capacitance cylinders produce a current that varies in proportion to the dielectric constant of the fluid passing through the plates. This method works well with any non-polar liquid which has a dielectric constant to density relationship that follows the Clausius-Mosotti Law.



[38]

Figure 3.3.15-1 Simmonds Precision Inferential Mass Flow System

The turbine element produces volumetric flow rate pulses and the compensator tubes form a capacitor that produces a current that varies in proportion to the dielectric constant of the fluid passing between the capacitor plates. Volume flow rate ( $V$ ) triggers a constant-pulse-width monostable which generates a signal whose frequency is proportional to volume flow rate. The density output signal ( $\rho$ ) is used as a reference voltage to the monostable such that the output is a series of constant-width-pulses whose height is ( $\rho$ ). The area under the pulse train is proportional to  $\rho$  and  $V$  which is a mass flow rate.  $M = V\rho$

The series of pulses from the monostable is filtered to produce an average DC level. Therefore, the output level is proportional to mass flow.  
(Figure 3.3.15-2)

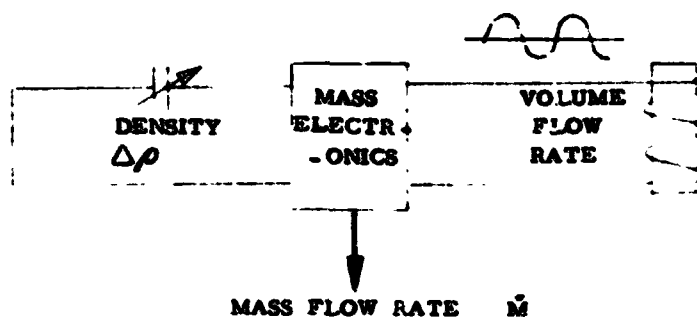


Figure 3.3.15-2 Simmonds Precision Flow Mass System Schematic

The entire system, the flowmeter, capacitance-density plates, and the mass electronics is packaged in one unit with the theoretical transfer function equal to:

$$\dot{M} = V \left[ \frac{1}{A} \frac{C_c}{C_o} - \frac{1-B}{A} \right]$$

$\dot{M}$  = fluid mass flow rate       $C_c$  = capacitance in fluid  
 $V$  = fluid volume flow rate       $C_o$  = capacitance in air  
 $A$  &  $B$  = constants

Simmonds Precision's literature appears to be misleading in that they reference the flowmeter for use with a "cryogenic" but limit "fuel environmental ranges" to - 65 F. This facility was not visited and it is not possible to evaluate their full capability. The advantages and disadvantages are those associated with any turbine type inferential mass flow measuring system using a capacitance to density method. Experience in density and inferential mass measurement areas provide them with more information than just the turbine meter manufacturers alone.



#### 3.4.16 Thermo-Systems, Inc.

Thermo-Systems has been building a thermal flowmeter (type five) device since 1961. (39) The design consists of self-heated probe exposed directly to the flowing stream. The energy transferred to the fluid is determined by its thermal conductivity, the mass rate of flow and the velocity distribution over the cross section of the tube in which the fluid flows.

Mass flow rate is most commonly related through the continuity equation as follows:

$$\dot{M} = \rho A V$$

$\dot{M}$  = Mass flow rate  
 $\rho$  = Flowing density  
 $V$  = Flowing velocity  
 $A$  = Cross section area of channel

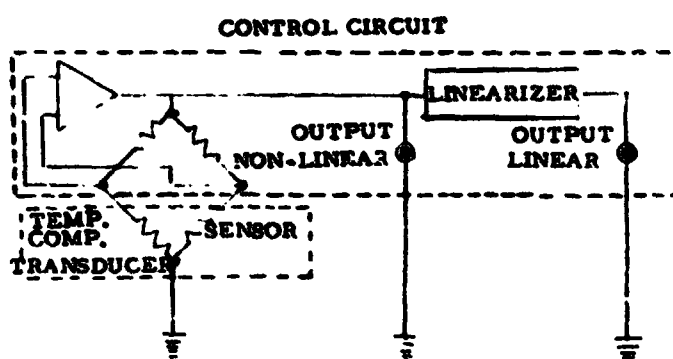
If channel area is constant, it is necessary to detect only the product  $\rho V$ . This quantity represents momentum per unit area of the fluid stream.

In the Thermo-Systems designed mass flowmeters, a platinum film sensor is located directly in the flow stream and connected electrically as shown in figure 3.3.16-1. This sensor is heated by current from the control circuit to a temperature above that of the fluid. The stream carries energy away from the sensor in proportion to the flow rate. A change in mass flow rate will tend to change the sensor temperature (resistance), but the amplifier senses any resistance change (due to bridge off balance) and feeds back more or less current to keep the bridge balanced. It can be shown that the power required to maintain this bridge balance is:

$$P = P_0 + k (\rho V)^a (t_s - t_e)$$

where:

$P$ = Power	$a$ = Exponent
$k$ = constant	$t_s$ = Sensor Temperature
$\rho$ = Density	$t_e$ = Fluid Temperature
$V$ = Velocity	
$P_0$ = Power with Zero Flow	



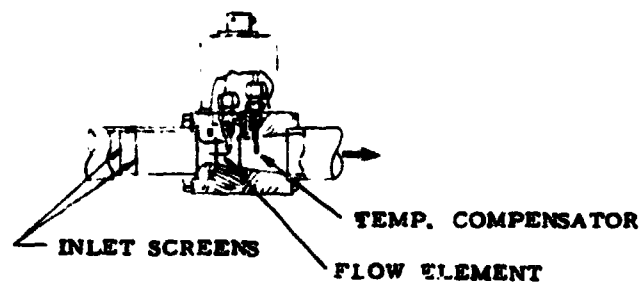
[40]  
Figure 3.3.16-1 Thermo-systems Thermal Mass Meter Schematic

The temperature compensating element is adjusted to give a constant voltage versus mass flow output from the control circuit even though environment temperature changes. It does this by changing sensor temperature in a manner to account for both changes in temperature differences ( $t_s - t_g$ ) and changes in temperature sensitive fluid properties.

For a given fluid media, the sensor measures local  $\rho V$ . Its position in the center of the nozzle allows an accurate and highly repeatable determination of total mass flow independent of temperature and pressure variations.

Two outputs are provided. One output is the non-linear signal directly from the bridge circuit, while the second output is linear with mass flow.

The flow transducer has a heated platinum film sensor on a support located at the throat of a smooth venturi. A quartz coating over the platinum film provides protection to the sensor. Inlet screens straighten flow and trap large particles. In clean fluids, the screens can be removed for lower pressure drop. The transducer has no moving parts and will withstand high levels of shock and vibration.[40] (Figure 3.3.16-2)



TRANSDUCER VENTURI SECTION

Figure 3.3.16-2 Thermo-systems Mass Meter Installation Cutaway

The measurement of mass flow rather than traditional volume flow has many advantages. Corrections for specific gravity, process temperature, media pressure, and compressibility are not needed to obtain meaningful data.

Direct mass flow measurement process balances are straight forward. Data reduction is greatly simplified. Control and transmission of flow data is reduced to one signal, simplifying operations.

Heated probe devices require relatively low power input, and are effective for low flows. Disadvantages include non-linear response and sensitivity to thermal conductivity, viscosity, and velocity distribution.

As no data is currently available on the cryogenic use of this type of flowmeter, testing would have to be accomplished before a determination of actual performance could be made.

### 3.4 DENSITOMETER CANDIDATES

Eleven of the sixteen flowmeter manufacturer candidates produce inferential mass flow measurement using a density measurement as one input. Of the eleven, four design and manufacture their own densitometer. Three of these densitometers use the capacitance principle that density is related to the dielectric constant by the Lorentz-Clausius-Mossotti equation. The other uses an oscillating vane driven at its natural frequency.

The capacitance densitometer can be constructed in several different ways. Usually it is fabricated as an integral part of the flowmeter and is shaped to provide flow straightening for the volumetric sensor portion of the meter. In some cases, this is a honeycomb configuration and in others it is a series of cylinders within cylinders. In all cases, suitable openings must be provided to allow fluid flow with a minimum amount of pressure drop and a maximum amount of laminar flow produced. The concept is predicated on the Lorentz-Clausius-Mossotti formula. This formula is considered to be an exact representation of the dielectric-density relationships for cryogenic fluids and all non-polar liquids and gases. (34)

$$\rho = \frac{nm}{N} = \frac{\bar{k}(\epsilon - 1)}{(\epsilon + 2)}$$

where:  $n$  = the number of molecules per unit volume  
 $N$  = Avogadro number  
 $m$  = molecular weight

$\frac{\epsilon - 1}{\epsilon + 2}$  = dielectric constant  
 $\bar{k}$  = Clausius-Mossotti ratio  
 $\bar{k} = 3m/4\pi N\alpha$  is a constant with  $\alpha$  as the molecular polarizability

and  $\rho$  = density of the media

The electronics section which is remotely located from the flowmeter converts the sensed quantity of density by performing an on-line computation from moment to moment. When this input is summed with the volumetric output of the flowmeter, a continuous output indication of true mass can be provided over the transition range from a liquid-biphase-to-gaseous state.

The vibrating diaphragm densitometer used by one of the inferential mass flowmeter candidates operates on the principle of Newton's second law; force is a product of mass times acceleration ( $F = Ma$ ). Vibration type densitometers represent a special case of the direct weight-volume measuring technique. Whereas direct weighing makes use of the earth's gravity as an acceleration reference, vibration type densitometers generate their own acceleration reference.

The heart of the densitometer is a thin vane which is symmetrically positioned within a thin-walled cylindrical support. By means of a remotely located driver and detector, the vane is driven at its natural frequency, causing the fluid surrounding it to be accelerated by its motion. The reaction of the fluid mass causes the vane to oscillate at a frequency which is a function of fluid density.

$$\rho = \frac{A}{f^2} + B \quad (1)$$



The densitometer may be used in either static or dynamic applications and such factors as fluid flow, pressure, temperature and viscosity have virtually no effect on its measurement precision.

The generalized characteristics of this type densitometer are:

- a. Their operation is digital in nature, since frequency is a measure of density.
- b. The constants (A) and (B) in equation (1) are independent of fluid properties; thus, the densitometer can be used for cryogenic liquids and gases.
- c. Their operation is independent of the earth's gravity; hence, the densitometer may be used in any position and in free space.
- d. They can be insensitive to flow line vibration and flow noise by operating at frequencies above or below noise frequencies.

At present, this is still a conceptual design under test and although the theoretical review has established a real capability, the empirical confirmation is as yet not available. [29]

### 3.5 APPLICATION OF AN AVAILABLE DESIGN

The following hypothetical problem is presented to illustrate more clearly the application of the flowmeter designs reviewed. The conclusions drawn in this manner are not an exact answer to the stated required values for a mass gas flowmeter. Since no flowmeter design exists that has demonstrated the capability of meeting these values, the probable flowmeter system design is defined, the questions to be answered are stated, and the testing facilities capability needs to be established.

The following is a hypothetical set of values for a mass gas flowmeter. Assume that we have an orbiting launch vehicle which is venting excess gas overboard.

- a. The fuel is gaseous hydrogen at a temperature between 33K and 89K.
- b. The system pressure is maintained at a constant 50 psia.
- c. The mass flow rate to be measured is 1 to 100 lb/sec.
- d. The output signal is to be digital.
- e. The total system weight and volume is to be carefully considered as the hardware is to be adaptable to a launch vehicle.



- f. The meter size is to be 4 inches in diameter and the run of pipe prior to entering the meter is of a length four times the meter.
- g. System transient accuracy shall be 1.0% or better.
- h. System steady state accuracy shall be 0.5% or better.
- i. The time constant shall be less than 10 milliseconds.

The establishment of the mass flow rate, the system pressure, the media and its temperature range defines the rangeability of the flowmeter. The density of hydrogen varies from  $0.058 \text{ lb/ft}^3$  to  $0.172 \text{ lb/ft}^3$  in the region under consideration. Since a mass flow rate of 1 to 100 lbs/sec has been picked, the flowmeter must be capable of measuring a range of approximately 300 to 1 in volumetric flow rate (fluid velocity) as described further.

The lowest velocity occurs at the smallest mass flow rate (one lb/sec) and highest density ( $0.172 \text{ lb/ft}^3$ ):

$$V_{\text{low}} = \frac{1 \text{ lb}}{\text{sec}} \div \frac{0.172 \text{ lb}}{\text{ft}^3} = 5.78 \frac{\text{ft}}{\text{sec}}. \text{ The highest velocity occurs at the largest mass flow } \left( \frac{100 \text{ lb}}{\text{sec}} \right) \text{ and lowest density } \left( \frac{0.058 \text{ lb}}{\text{ft}^3} \right):$$

$$V_{\text{HI}} = \frac{100 \text{ lb}}{\text{sec}} \div \frac{0.058 \text{ lb}}{\text{ft}^3} = 1724 \frac{\text{ft}}{\text{sec}}. \quad [41] \text{ Therefore, the total range in fluid velocity or volumetric flow rate that must be covered is 1724 to 5.78, or } 296.7 \text{ to } 1. \text{ This is an extremely large rangeability requirement but since the object of this exercise is to illustrate the problems involved in determining a flowmeter's use, we will consider it a valid requirement.}$$

With this above data established, we now address to the three basic questions involving the 16 candidates:

- a. What flowmeters have the potential capabilities of meeting these requirements?
- b. What flowmeters have previous experience to substantiate their capability claims?
- c. What test program and effort will be necessary to achieve the accuracy required?

The four mass movement types can be eliminated for three reasons, all of which are inter-related. Their rangeability is low, at best 15 to 1. They require mass flow rates in excess of the one lb per second range established and final the ratio of inertia forces to viscous forces must be quite high, i.e.:  $N_{Fr} = 11,000$  in one case.



The Bluff body candidate has a maximum rangeability of 100 to 1 and requires a strong shedding vortex which exceeds a  $Re > 10,000$ . Low velocities of hydrogen gas such as the required 5.78 ft<sup>3</sup>/sec would produce insufficient inertia force.

The two drag body designs consist of a cantilevered beam with strain gages as the sensor and a force rebalancing system. The beam and strain gage design has a rangeability of only 10 to 1. The force rebalancing rangeability is 20 to 1. As to the ability of these types to measure flow as low as one lb/sec. at a density of 0.058 lb/ft<sup>3</sup>, no information is available.

The thermal meter and the turbine meter, both have designs which have sufficient rangeability. The output of the thermal meter is directly in mass but to digitize it the signal must be signal conditioned to a higher voltage level. Although the turbine meter output is digital, it must be influentially combined with density to give mass output. The time constants of both types are close enough to make no difference in evaluating the two. (3.6.3) In the area of size and weight, the thermal system probably has an advantage of between 1.5 and 2.0 times over that of the turbine meter inferential system.

Based on the relatively small amount of data available on the use of the thermal meter at a cryogenic temperature and the relatively large amount of data available on the turbine meter, the transient and steady state total accuracies differ greatly. This difference appears to be in error close to 100 times greater for the thermal meter over the turbine meter. Although the turbine meter designs themselves differ greatly from manufacturer to manufacturer, if the most promising design is selected with the appropriate densitometer, an accuracy of 0.10% is claimed. Past experience with one thermal meter design and literature from the other manufacturer indicate an accuracy as low as 10%. A reason for considering the thermal meter is that the design concept is simple and in one case, nothing need protrude in the flow stream and the manufacturing cost should be an order of magnitude less than the turbine meter - densitometer design.

Theoretically, the thermal meter principal should work over the designed range by using specialized calibration techniques and with further work and careful installation design, the potential accuracy could approach 1%.

Returning to the three questions regarding the sixteen candidates previously stated, we can note the following:

- a. The thermal and turbine meter have a potential capability for meeting the requirements stated.
- b. The turbine meter, specifically the dual blade "piggyback" type, has by far and away the most comprehensive data available on measuring mass gas flow at a cryogenic temperature. Although this data is at the transition point between a liquid and a gas (20-23 F), it should hold true in a gaseous state only.



- c. The thermal meter would require a complete redesign, an installation and test with a cryogenic gaseous media, a modification based on test results and further verification testing. The "piggyback" turbine meter and capacitance densitometer could be tested as designed in a cryogenic gaseous media over the temperature range of interest. Verification of its capability would in effect qualify it for use.

The dual turbine meter and capacitance densitometer is the only candidate system capable of meeting the established requirements, and although it requires considerable additional testing and perhaps some redesign, no other system has as much potential for meeting the values defined for a mass cryogenic gas flowmeter.

### 3.6.1 FLOWMETER MANUFACTURER SURVEY TABLE

MANUFACTURER	MEDIUM	TEMP ( K )	TYPE-SYSTEM
AIR PRODUCTS	GAS	394	VARIABLE AREA, ROTAMETER
AMERICAN STANDARD	GAS	78/533	SWIRLMETER
BADGER	LIQ.	358	TURBINE METER
BADGER	--	--	DIFFERENTIAL PRESSURE
BAILEY	LIQ/GAS	244/344	DIFFERENTIAL PRESSURE
BAILEY	LIQ/SLURRY	450	VARIABLE AREA, ROTAMETER
BAILEY	SOLIDS	277/333	INFERENCE MASS
BENDIX	LIQ/GAS	20/422	FORCE-SCREEN
BRISTOL	LIQ/GAS	--	DIFFERENTIAL PRESSURE
BROOKS	LIQ/GAS	588	VARIABLE AREA, ROTAMETER
BROOKS	LIQ.	19	TURBINE METER
BROOKS	LIQ/SLURRY	350/422	ELECTROMAGNETIC
BUBBLE-O-METER	GAS	273/339	SOAP FILM DISP.
C.G.S/DATAMETRICS	LIQ/GAS	273/349	HOT SENSOR, ANEMOMETER
COX	LIQ/GAS	19	TURBINE METER
DANIEL	LIQ.	16/810	TURBINE METER
DIETERICH ST'D	GAS/LIQ/ STEAM	227/810	DIFFERENTIAL PRESSURE
DWYER	LIQ/GAS	339	VARIABLE AREA, ROTAMETER
EASTECH	LIQ/GAS	CRYO/477	BLUFF-BODY
ELECTRO DEV. CORP.	LIQ/GAS	20/90	MOMENTUM MASS
ELECTROSYN	LIQ/GAS	277/322	BOURDON TUBE
FISHER AND PORTER	LIQ/GAS/ SLURRY	5/533	TURBINE METER



### 3.6.1 FLOWMETER MANUFACTURER SURVEY TABLE

MANUFACTURER	MEDIUM	TEMP ( K)	TYPE-SYSTEM
FISHER AND PORTER	LIQ/SLURRY	273/455	ELECTROMAGNETIC
FLOW CON	LIQ/SLURRY	14/533	TURBINE METER
FLOW TECH.	LIQ/GAS	14/450	TURBINE METER
FLUID DATA	LIQ.	89/477	ULTRASONICS
FOXBORO	LIQ.	78/333	MOMENTUM MASS
FOXBORO	LIQ/GAS	19/810	TURBINE METER
GEMS	LIQ.	355	VARIABLE AREA ROTAMETER
GENERAL ELECT.	LIQ/GAS	20/90	MOMENTUM MASS
GENERAL ELECT.	LIQ/GAS	244/358	DIFFERENTIAL PRESSURE
GILMONT	LIQ/GAS	255/373	VARIABLE AREA ROTAMETER
GURLEY	LIQ.	273/339	TURBINE METER
HALLIBURTON	LIQ.	200/678	TURBINE METER
HASTINGS-RAYDIST	GAS	200/810	THERMAL
HONEYWELL	LIQ/GAS	366	DIFFERENTIAL PRESSURE
HONEYWELL	LIQ/GAS	19	DRAG BODY
IND. MEAS.	LIQ.	255/353	POSITIVE DISPLACEMENT
IN-VAL-CO	LIQ.	200/700	TURBINE METER
ITT BARTON	LIQ/GAS	19/810	TURBINE METER
ITT BARTON	LIQ/GAS	222/366	DIFFERENTIAL PRESSURE
KINGMANN-WHITE	LIQ/GAS/VAPOR	WATER	DIFFERENTIAL PRESSURE
KONTES	GAS	343	DIFFERENTIAL PRESSURE
KONTES	GAS	344	VARIABLE AREA, ROTAMETER
L&N	LIQ/GAS	239/344	ELECTROMAGNETIC
LIBRASCOPE	GAS	227/333	FLOW COMPUTER
LINDSEY	LIQ/GAS/SLURRY	33/810	TURBINE (OUT OF BUS.)
LIQUID CONTROLS	LIQ.	222	POSITIVE DISPLACEMENT
MACE	LIQ/GAS	222/477	--
MANOSTATE	LIQ/GAS	200/477	VARIABLE AREA, ROTAMETER



### 3.6.1 FLOWMETER MANUFACTURER SURVEY TABLE

MANUFACTURER	MEDIUM	TEMP ( K )	TYPE-SYSTEM
MATHESON	LIQ.	394	VARIABLE AREA, ROTAMETER
MEDCO	GAS	294	VARIABLE AREA, ROTAMETER
MFG-O-METER	LIQ.	--	DIFFERENTIAL PRESSURE
MERIAM	--	233/700	LAMINAR FLOW ELEMENT
NATIONAL INSTR.	GAS	255/378	DIFFERENTIAL PRESSURE
NEPTUNE	LIQ.	--	TURBINE METER
QUANTUM DYNAMICS	LIQ/GAS	3/511	TURBINE METER
RAMAPO	LIQ/GAS	219/810	VARIABLE AREA, ROTAMETER
RAMAPO	LIQ/GAS	75/616	STRAIN GAGE DANC BODY
ROBINSON	ANY	--	DIFFERENTIAL PRESSURE
ROCKWELL	LIQ.	372	TURBINE METER
ROSEMOUNT ENG.	GAS/LIQ.	158/311	THERMAL MASS
ROTRON	LIQ/GAS	233/450	VORTEX
SCHROEDER	LIQ.	277/378	DIFFERENTIAL PRESSURE
SENTRY	LIQ.	--	TURBINE METER
SIMMONS PRECISION	LIQ.	20/422	TURBINE METER
STATHAM	BLOOD	289/311	ELECTROMAGNETIC
TAYLOR	LIQ/SLURRY	255/394	ELECTROMAGNETIC
TAYLOR	LIQ. GAS/SLURRY	233/810	DIFFERENTIAL PRESSURE
TECH VERSATRONICS	GAS	230/339	THERMAL MASS
THERMAL INST. CO.	GAS/LIQ.	TO 922	THERMAL MASS
THERMO-SYSTEM INC.	GAS/LIQ.	227/366	THERMAL MASS
TYLAN	GAS/LIQ.	219/344	DIFFERENTIAL FLOW
WALLACE & TIERNAN	LIQ/GAS	394	VARIABLE AREA, ROTAMETER
WAUKEE	GAS	339	VARIABLE AREA, ROTAMETER



### 5.6.2 CANDIDATE DESIGN COMPARISON TABLE

CANDIDATE	TYPE OF SYSTEM AND PRINCIPAL	DENSITOMETER
		MFG'D TYPE
BENDIX	DRAG BODY-FORCE RE-BALANCING	YES - DIELECTRIC- TO-DENSITY
COX INST	TURBINE METER - BLADE AND RF PICKOFF	NO - VOLUMETRIC OUTPUT ONLY
EASTECH	BLUFF BODY - VORTEX SHEEDING	NO - VOLUMETRIC OUTPUT ONLY
ELECTRO DEV. CORP.	MOMENTUM, ANGULAR - MASS $\propto$ TIME	NOT NECESSARY, TRUE MASS OUTPUT
FISHER & PORTER	TURBINE METER - BLADE AND RF OR MAG PICKOFF	NO - VOLUMETRIC FLOW ONLY
FLOW TECH	TURBINE METER - BLADE AND RF OR MAG PICKOFF	NO - VOLUMETRIC FLOW ONLY
FOXBORO	MOMENTUM, ANGULAR - TORQUE AND ANGULAR SPEED	NOT NECESSARY, TRUE MASS OUTPUT
	TURBINE METER - BLADE AND MAG PICKOFF	NO - VOLUMETRIC FLOW ONLY
GENERAL ELECTRIC	MOMENTUM, ANGULAR - TORQUE, RADII AND ANGULAR SPEED	NOT NECESSARY, TRUE MASS OUTPUT
HASTINGS-RAYDIST	THERMAL - HEAT TRANSFER	NOT NECESSARY, TRUE MASS OUTPUT
HONEYWELL	MOMENTUM, LINEAR - DAMPING RATIO TO MASS	NOT NECESSARY, TRUE MASS OUTPUT
ITT BARTON	TURBINE METER - BLADE AND MAG PICKOFF	YES - OSCILLATING VANE
QUANTUM DYNAMICS	TURBINE METER - BLADE AND RF PICKOFF	YES - DIELECTRIC- TO-DENSITY
RAMAPO	DRAG BODY - STRAIN GAGE PICKOFF	NO - VOLUMETRIC FLOW ONLY
ROSEMOUNT	THERMAL - HEAT TRANSFER	NOT NECESSARY, TRUE MASS OUTPUT
SIMMONS PRECISION	TURBINE METER - BLADE AND PICKOFF	YES - DIELECTRIC- TO-DENSITY
THERMO SYSTEMS	THERMAL - HEAT TRANSFER	NOT NECESSARY, TRUE MASS OUTPUT

3.6.3 ACCEPTABLE FLOWMETER TABLE

CANDIDATE NAME	ACCURACY (%)	REPEAT (%)	RESOLUTION	TIME CONSTANT	RANGEABILITY
BENDIX, INST. & LIFE SUPPORT DIV.	0.50	D.N.A.	D.N.A.	400 MSEC	10:1
COX INSTRUMENTATION	1.00	0.10	.007 GPM	5.0 MSEC	100:1
EASTECH INCORPORATED	0.25	0.10	1 GPM	2.0 MSEC	100:1
ELECTRO DEVELOPMENT CORPORATION	1.00	D.N.A.	D.N.A.	D.N.A.	D.N.A.
FISHER AND PORTER	0.25	0.10	.07 GPM	5.0 MSEC	20:1
FLOW TECHNOLOGY, INC.	0.20	0.10	0.1 GPM	3.0 MSEC	20:1
FOXBORO INST. (ANGULAR MOMENTUM TURBINE)	1.00 0.20	D.N.A. 0.10	D.N.A. D.N.A.	D.N.A. 25 MSEC	D.N.A. 24:1
GENERAL ELECTRIC COMPANY	1.00	1.00	D.N.A.	D.N.A.	10:1
HASTINGS-RAYDIST	2.00	0.50	D.N.A.	D.N.A.	D.N.A.
HONEYWELL, INC.	1.00	0.50	D.N.A.	3.0 MSEC	10:1
ITT BARTON	0.25	0.10	.004 GPM	3.0 MSEC	D.N.A.
QUANTUM DYNAMICS, INC.	0.10	0.15	1/3 CC	0.5 MSEC	500:1
RAFAPO INSTRUMENT COMPANY	0.50	0.10	0.1 GPM	1.0 MSEC	10:1
ROSEMOUNT ENGINEERING COMPANY	+6.00 -4.00	0.50	D.N.A.	2.0 MSEC	D.N.A.
SIMMONS PRECISION	1.00	0.10	.02%	0.5 MSEC	20:1
THERMO-SYSTEMS INCORPORATED	5.00	0.10	D.N.A.	1.0 MSEC	500:1

NOTE: THESE VALUES ARE ONLY AN INDICATION OF CAPABILITY.  
FOR A SPECIFIC NEED EACH OF THESE CANDIDATES MUST  
BE RE-EVALUATED.

D.N.A. = DATA NOT AVAILABLE





#### 4.0 CRYOGENIC LIQUID DETECTION MEASUREMENT TECHNOLOGY

The primary objective of this report was to present the available propellant gaging systems applicable to future space vehicles. The report gives a brief description of each system including theory of operation, accuracy, stability, power requirements, and the gravitational environment in which the system is designed to perform.

Propellant gaging, under positive gravity conditions, is generally simplified due to the presence of an acceleration vector which allows prediction of the propellant location and shape within the confines of the tank. Point sensors of the ultrasonic, optical, or heated wire type are all capable of accurate propellant level (volume) measurements. Propellant volume measurement devices of the echo-ranging and capacitance type which provide continuous measurements are also adaptable. These systems, however, are useful for propellant quantity indication only when a dominant vehicle acceleration is coincident with the vehicles measuring system which allows prediction of the propellant location. The techniques of gaging propellants randomly oriented within the tank, i.e., under propellant sloshing and zero g conditions, poses a more complex problem.

#### 4.1 TECHNICAL DISCUSSION

The general propellant orientation in space corresponds to the Bond number behavior, where the Bond number provides a comparison between gravitational and capillary effects:

$$Bo = \rho \frac{g L^3}{\sigma} \quad [42]$$

where  $\rho$  is the fluid density,  $g$  the acceleration,  $L$  a characteristic dimension of the system (length of the tank), and  $\sigma$  the surface tension. For low Bond number systems, capillary forces dominate the hydrostatic propellant behavior, while for high Bond number systems, acceleration forces dominate the behavior. Therefore, even in extremely low acceleration environments, forces exist which prevent the propellant from assuming random orientations.

Theoretical studies indicate that, in capillary dominate regions, the minimum energy propellant configuration is one in which the vapor phase is present in spherical bubbles. Energy considerations further indicate that total surface energy is minimized if the vapor bubbles collect into a single large bubble, and additionally that the bubbles tend to attach themselves to the tank wall. Low acceleration experiments generally verify that such minimum energy configurations occur, though some experiments indicate the metastable equilibrium situations occur in which small bubbles group around and attach themselves to a larger bubble, much like a bunch of grapes.

Thus, completely random orientations of propellant within a tank are statically unstable for low Bond numbers situations, capillary forces cause the formation of a spherical bubble or a cluster of bubbles. For high Bond number situations, acceleration forces although small tend to orient the propellant so that a single relatively flat liquid-vapor interface exists. Such propellant behavior is of fundamental importance with regard to the design of propellant mass measurement systems.



Basic zero g propellant quantity gaging is readily integrated into all phases of propellant management. The four pertinent applications are loading, gaging, utilization and center of gravity control.

To monitor and control the level of propellants during the loading operation, the system output is monitored by ground instrumentation which in turn controls the loading control valve. Fast fill, medium fill and slow fill rates, or proportional flow, can be obtained based upon quantity information received from the propellant measurement system.

During a powered flight the outputs from the two gages measuring fuel and oxidizer on the respective tanks can be compared in a propellant utilization computer-comparator. The comparator determines the sense and magnitude of mixture ratio deviation and repositions the engine propellant utilization valve to compensate for this deviation. The result is close control of the engine mixture ratio and minimum propellant residual at the end of flight.

The system output can be directly used for propellant volume indication by readout on a cockpit instrument and/or by ground monitoring through use of telemetry.

The system outputs obtained from multi-tank vehicles provide center of gravity control. Either manual, semi-automatic or automatic control may be accomplished. The center of gravity control feature allows maintenance of a fixed center of gravity or permits relocating the center of gravity.

#### 4.2 EVALUATION OF AVAILABLE DESIGNS

The results of the study have produced eleven different propellant gaging systems offered by nine manufacturers. Of these, five systems are applicable only to positive g environments, and seven are applicable to both positive and zero g environments. These systems can be further categorized into five types: Point Sensors, Capacitance Probes, Radio Frequency, Infrasonic, and Nucleonic. Point sensors and capacitance probes are only useful in positive g environments. The infrasonic and nucleonic systems are applicable in zero g environments; however, they are still in the development stage and at this time have a weight disadvantage to obtain the required accuracy.

The use of the more standard coaxial cylinder capacitance sensor system for continuous gaging of propellants is not practical due to the capillary rise that occurs at low gravity conditions. The capillary rise for LH<sub>2</sub> and LOX is on the order of 40 inches and 20 inches, respectively, for capacitance sensors similar to those used on the Saturn S-II stage.

Because future space missions encompass two distinct regimes of gravitational acceleration, no single concept of propellant gaging is entirely satisfactory. The operations include zero gravity conditions during coast periods experienced in earth orbit, and high gravity conditions during vehicle thrust. Consequently, a combination of propellant gaging concepts is required to provide propellant mass or volume measurements. The results of the study indicate the radio frequency sensor system is best utilized for propellant monitoring during zero gravity periods, and a combination of the RF and the discrete level sensor systems is best utilized during high gravity periods.

#### 4.3 SURVEY RESULTS OF CURRENTLY AVAILABLE SYSTEMS

##### 4.3.1 Acoustica Ultrasonic Sensor System [43]

The Acoustica Ultrasonic system for liquid level gaging operates on the principle of continuous ultrasonic echo-sounding. The system consists of a piezoelectric crystal transducer and stillwell assembly with a remote control unit. Liquid level is gaged by periodically measuring the time required for an ultrasonic pulse to travel from the transducer to the liquid surface and back again to the common transmit-receive transducer (see Figure 4.3.1-1).

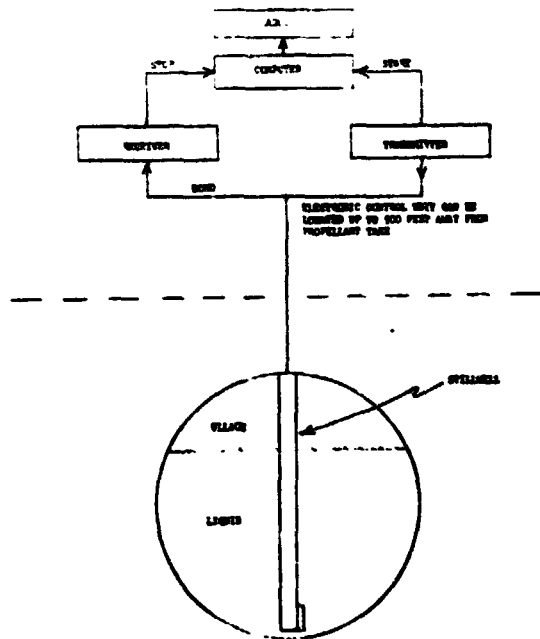


Figure 4.3.1-1 Acoustica Ultrasonic Sensor System



In operation, a pulsed electrical input from the transmitter causes the transducer to generate an ultrasonic pulse. This pulse travels to the liquid-gas interface where part of the energy is reflected back to transducer and receiver-readout device. The time required for the pulse to travel is measured and converted to an equivalent distance from the transducer location to the liquid level above the transducer. This system requires only the stillwell and transducer to be exposed to the liquid/gas inside the tank.

Accuracy	+0.50 inch
Temperature Range	-320 to +300 F
Pressure Range	0 to 5000 psia
Power Requirement	5 watts
Response	25 milliseconds

For zero g application, this system could not gage the liquid level. The capillary forces will draw the liquid into the stillwell causing the transducer to indicate full tank at all times. For positive g application, this system would work satisfactorily.

#### 4.3.2 Acoustics Discrete Level Sensor System [44]

The Acoustics discrete level system utilizes a resistance type sensing element consisting of a .0005 inch diameter gold plated platinum wire grid. The wire is powered by a constant current to maintain its temperature at a level slightly higher than its surrounding environment. Since the resistance of the wire varies as a function of temperature, any change in the medium in contact with the sensing element, whether liquid-to-vapor or vapor-to-liquid, causes a relatively large and almost instantaneous change in resistance. This resistance change is used to operate a solid state switch in the control unit.

Accuracy	+0.1 inch
Temperature Range	-430 to +300 F
Pressure Range	0 to 5000 psia
Power Requirement	7 watts/unit LH <sub>2</sub> 3.5 watts/unit LOX
Response	50 milliseconds

For zero g application, this type of measuring system does not have the capability of measuring mass within a tank. However, under positive g conditions this technique is very good for determining a certain loading level, if the alignment of sensors is in the direction of the g force.

#### 4.3.3 Acoustics Infrasonic Sensor System [43]

Acoustics' infrasonic zero g propellant gaging system has been developed to measure the volume of liquids in a low acceleration environment. The liquid volume is obtained by measuring the gas volume and subtracting it from the known empty tank volume. The gas volume is found through a dynamic acoustic measurement of the ullage compliance. This is accomplished by a method of comparison where the compliance of the unknown gas volume in the propellant tank is compared to the compliance of the same gas in a known

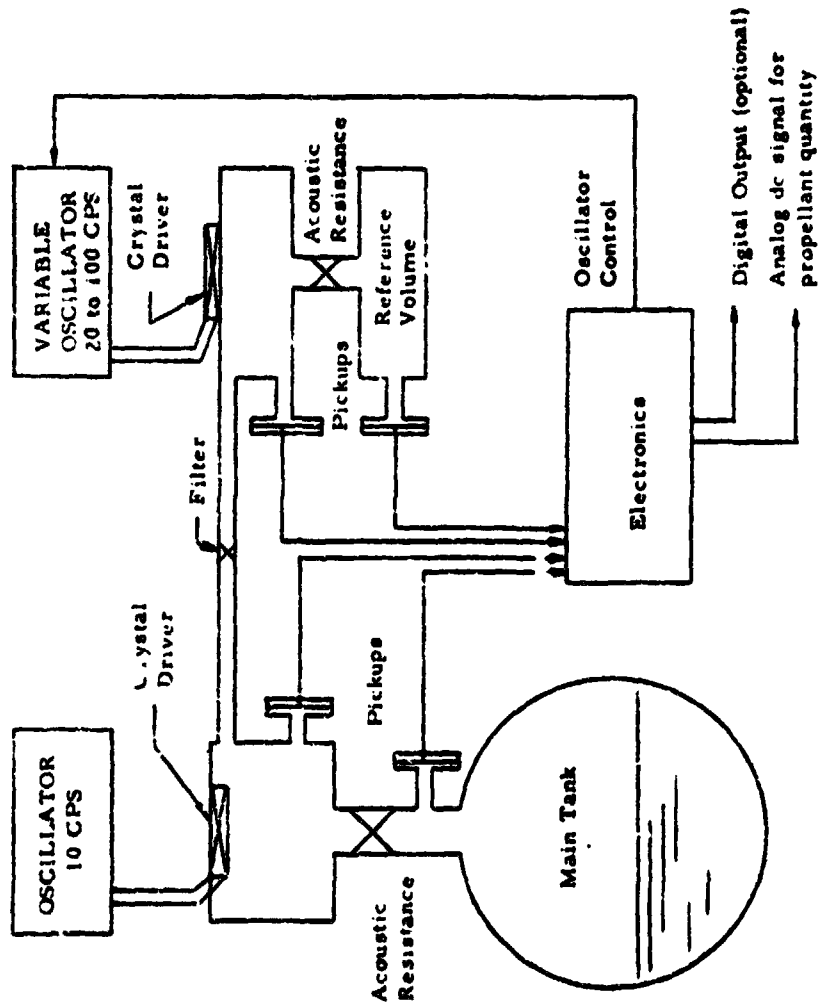


Figure 4.3.3-1 Acoustica Infrasonic Sensor System

reference volume. A dynamic reference method is used to eliminate the need for knowing the changes in pressure, temperature and ratio of specific heats of the gas. The comparison is accomplished through an acoustic bridge arrangement of the two volumes and two acoustic resistances. A schematic diagram of the acoustic system is shown in Figure 4.3.3-1. The volumes represent acoustic compliances, and the acoustic resistances are composed of fine mesh screens. The source of dynamic pressure in the main tank is an electrodynamic driver. A dynamic pressure pickup in each volume provides the necessary information signals.

Accuracy	+1.0 to +2.0%
Temperature Range	Full to Empty
Pressure Range	-430 to +300 F
Power Requirements	0 - 50 psia
Response	50 watts
	5 to 10 seconds

This system has demonstrated feasibility for bladder-type applications wherein the gage is used to determine gas ullage volume and where liquid entrapment, in the gage, is not a problem. If liquid entrapment can be eliminated, this system could provide propellant gaging under zero g environment with relatively good accuracies.

#### 4.3.4 Bendix Corporation Cryogenic Optical Sensors

The Bendix Corporation optical sensors have been used in LOX and JP4 on the S-IC stage for Apollo missions. Recent improvements have enabled their use in LH<sub>2</sub>. The basic principle of operation can be understood by considering the sketch shown in Figure 4.3.4-1.

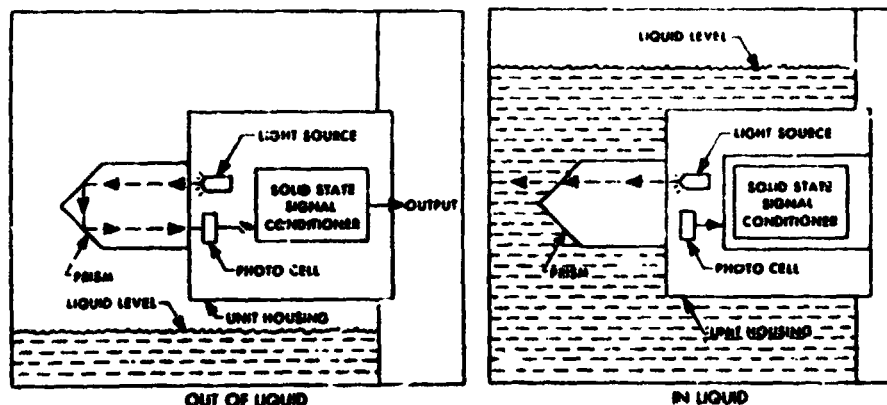


Figure 4.3.4-1 Bendix Cryogenic Optical Sensor



The optical sensor consists of an internal light source, a reflecting prism, a light sensitive pickup cell and electronic signal conditioning circuitry. Light rays from the light source are directed down one side of the transparent cylindrical prism which is located at the liquid level sensing point.

When liquid is present at the end of the prism, most of the light passes through the prism - liquid interface, and is dissipated in the liquid. When gas is present, the changed index of refraction at the interface causes most of the light to be reflected across the prism face and through the transparent cylinder. This light impinges on a photo cell, which in turn produces an electrical output which is used to drive a transistorized switching amplifier.

Accuracy	+3/32 inch
Temperature Range	-320 to 160 F
Pressure Range	140 psia
Power Requirements	6 watts
Response	50 milliseconds

This is a point sensor type system and is limited to positive  $g$  applications. For propellant loading and propellant depletion under positive acceleration, this system will give very accurate results if the sensors are aligned compatible with the direction of the  $g$  force.

#### 4.3.5 Bendix Corporation Radio Frequency Sensor System [45]

The Bendix Corporation radio frequency (RF) quantity gauging system operates by introducing microwave energy into a tank so as to illuminate it by setting up electromagnetic fields throughout the entire volume of the tank. The tank interior is a dielectric region completely surrounded by conducting walls. Such a system is called a cavity, and the resonant solutions are the normal theoretical modes of the cavity. Figure 4.3.5-1 shows the RF gauging system in block diagram form.

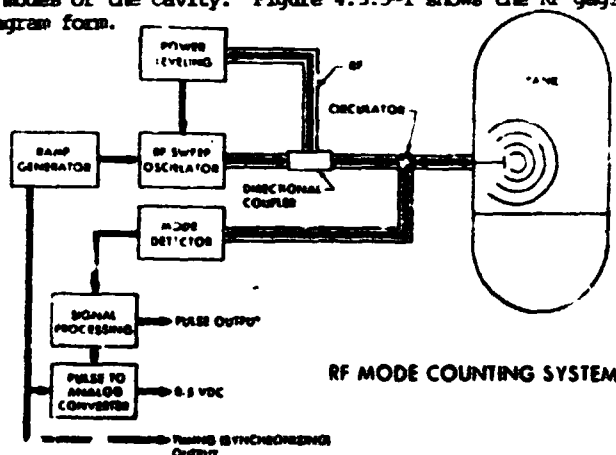


Figure 4.3.5-1 Bendix Radio Frequency Sensor System



The RF section consists of a voltage tunable RF sweep oscillator, an attenuator, a low-pass filter which cuts off at the maximum desired output frequency, and a directional coupler which provides a sample of the RF power level. This level is held constant by detecting it at the directional coupler and using the detected power to control a power leveling circuit. The power leveling circuit controls the DC bias of the RF sweep oscillator. The RF energy is coupled into the tank probe through a circulator and coaxial cable. The tank probe is a wide band spiral antenna. The RF energy reflected from the probe is detected at the third port of the circulator using a mode detector (crystal diode). This detected energy contains the mode information. The signal conditioning circuit produces a constant-width, constant-amplitude pulse for each detectable mode. This provides a train of pulses which can be counted electronically or fed into a Pulse to Analog Converter to produce an analog output voltage.

Accuracy	+10.0 to 1.0%, Full to Empty
Temperature Range	-430 to 300 F
Pressure Range	0 - 100 psia
Power Requirement	30 watts
Response	30 milliseconds

This system is applicable to both zero g and positive g conditions. It has demonstrated feasibility for measuring liquid volume under zero g and propellant slosh conditions. This system would be an excellent choice providing more development work is done to improve linearity and accuracy.

#### 4.3.6 Conrac Corporation Radiation Sensor System

Conrac's radiation system is a monoenergetic gamma transmission system which incorporates a source-detector pair across the tank length. Each source is collimated to a 5 degree half angle to impinge only on its matched detector to reduce cross-talk. The detector is a Sodium Iodide (Thallium-activated) scintillator crystal (NAT TI) which activates a photomultiplier tube (PMT). The PMT's output (which is equivalent to the mass between the source and the detector) is summed with the other outputs to indicate the amount of mass within the tank.

Accuracy	+1.5 to +0.5% Full to Empty
Source	Cs 137
Source Strength	550 millicuries
Power Requirements	27 watts

#### 4.3.7 Industrial Nucleonics Radiation Sensor System [46]

Industrial Nucleonics recommends the use of two different type (mass and volume) nucleonic gaging systems. For a mass sensitive measurement INC recommends a monoenergetic gamma transmission system which incorporates a source-detector pair across the tank length. Each pair has an output (equivalent to the mass between the source and the detector) which is summed with the other outputs and the total is an indication of the mass in the tank.

For a volume sensitive measurement, DDC recommends a back scatter shadow system which uses gamma radiation reflected from the liquid to activate the detector for an output. This system measures the volume of liquid surrounding the source-detector pair and is quite similar to a point sensor system.

Accuracy	+1.5%
Source	Cs 137
Source Strength	1.5 curies
Power Requirements	40 watts

For zero g application, the monoenergetic gamma transmission system would work providing there are enough source-detector pairs to cover the volume of the tank. The backscatter shadow system probably will not work for zero g application but would work for positive g environment.

#### 4.3.8 Simmonds Precision Coaxial Cylinder Capacitance System [47]

The Simmonds precision system is based on redundant sensing systems. The primary system employs axial capacitance tubes in the tanks to continuously measure propellant mass. The backup system employs any number of individual impedance sensors spaced along the length of the tank. In the primary system for measuring propellant quantity, the sensor consists of two concentric conducting cylinders along the axis of the tank (reference Figure 4.3.8-1).

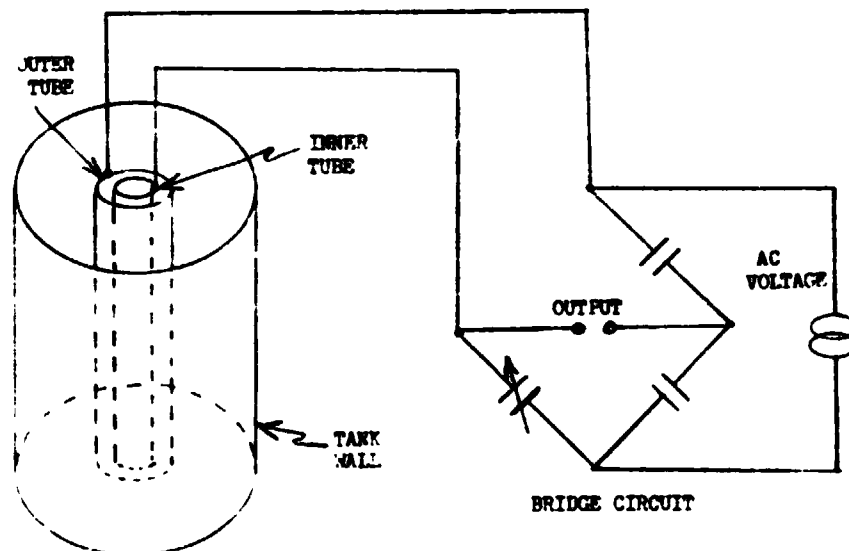


Figure 4.3.8-1 Simmonds Precision Coaxial Capacitance System

As the propellant is depleted, the capacitance between the two cylinders changes linearly with the volume of the propellant. The varying capacitance unbalances a bridge circuit. This unbalance is continuously and automatically nulled by a servodriven potentiometer. The position and corresponding output voltage of the potentiometer, therefore, analogs of the propellant volume. The backup sensing system is somewhat more complex. Each point sensor is a ring in the horizontal plane. The sensors are mounted on a tube which runs vertically along the length of the tank.

The impedance of each sensor depends on whether it is covered by the propellant. A sensor forms half of a capacitive bridge (reference Figure 4.3.8-2) with a fixed capacitance forming the other half.

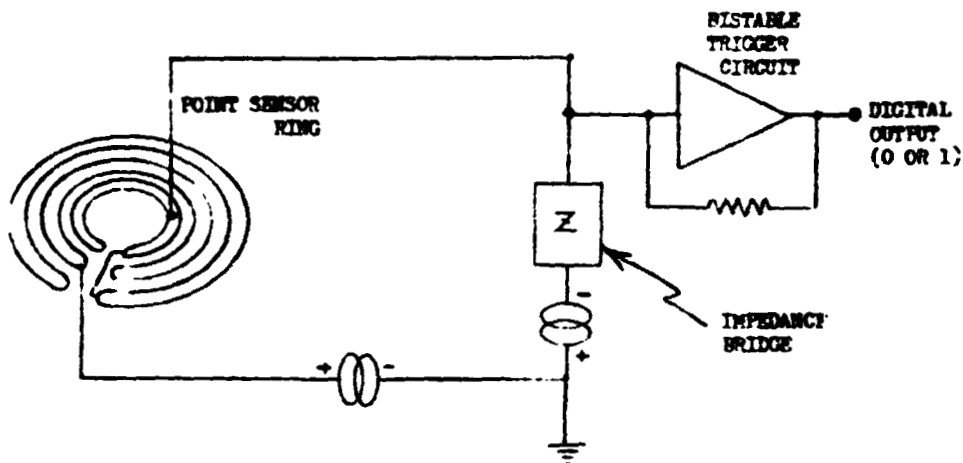


Figure 4.3.8-2 Simmonds Precision Point Sensor Ring System

As the propellant level drops, sensors are uncovered one by one. Trigger circuits sense the output of each bridge and change state as the sensor is uncovered.

Accuracy	+1.0 to +2.0% Full to Empty
Temperature Range	-430 to +300 F
Pressure Range	0 - 50 psia
Power Requirement	7 watts
Response	5 to 10 seconds



For zero g application, this system could not function as a gaging system, because the capillary action of the fluid would fill the probe to give a full output at all times. However, this system is an excellent system for a positive g environment (Bond number  $>4$ ;  $g$  levels  $>2 \times 10^{-5}$ ).

#### 4.3.9 Trans-Sonics Corporation Peripheral Capacitance System [48]

The Trans-Sonics peripheral capacitance system utilizes 16 electrodes that are panels which attach to the inside tank wall so that the whole tank becomes the dielectric of a capacitor. The shapes and potentials of the electrodes are adjusted so that the interior electric field is approximately uniform throughout the tank, insuring equal weighting to all regions, regardless of how the liquid is distributed.

Accuracy	+2.0%
Temperature Range	-430 to +165 F
Pressure Required	0 - 100 psia
Power Requirement	50 watts

This system is trying to measure too small a capacitance. Consequently, noise and stray capacitance will cause additional development problems. For zero g application, this system could work providing the above-mentioned problems are solved.

#### 4.3.10 TRW Infrasonic Sensor System [49]

The TRW system is a resonant infrasonic gaging system which utilizes a small oscillating pressure change to detect the volume of the ullage gas. The system consists of a driver piston, a follower piston (or diaphragm), and a pressure transducer. The volume between the driver and the follower makes up the reference cavity which houses the pressure transducer. At some frequency to the driver, the force required to compress the reference cavity will be balanced by the restoring force, caused by compression of the ullage gas, and the system will be in resonance.

The resonant frequency is related to the amount of ullage gas; therefore, one can measure the quantity of propellants by measuring the resonant frequency.

Accuracy	+1.0 to +2.0% Full to Empty
Temperature Range	-430 to +300 F
Pressure Range	0 - 50 psia
Power Required	7 watts
Response	5 to 10 seconds

This system is applicable to zero g conditions. Its accuracy is adequate, however, the response time is slow. This system would be excellent for the coast modes used during long space voyages.



#### 4.3.11 Tyco Laboratories Radiation Sensor System [50]

Tyco Laboratories radiation sensor system uses a noncollimated monoenergetic gamma transmission system which places a point source in the center of the tank and measures the radiation at the tank walls. The prototype that was tested had only two detectors 180 degrees apart. For greater accuracy, additional detectors and a larger electronics package to integrate the outputs from the detectors could be added.

Accuracy	+2.0%
Source	AM 241
Source Strength	31 millicuries
Power Requirement	7 watts

This system could be adapted for zero g applications providing enough detectors were installed to cover the entire volume of the tank. This would result in a very large weight penalty and would not be practical.

#### 4.3.12 United Controls Discrete Level Sensor System

United Controls discrete level sensor system uses a "constant resistance" wire element and an electronic control module. A series of sensors are mounted in a stillwell that extends over the length of the tank. As each sensor is immersed, a discrete signal is developed to indicate propellant level in the tank.

Accuracy	+0.06 inch
Temperature Range	-425 to +250 F
Pressure Range	0 - 500 psia
Power Requirement	7 watts/unit
Response	16 milliseconds

For zero g application, this type (point sensor) measuring system does not have the capability of measuring mass within a tank. However, under positive g conditions, this technique is very good for determining a certain loading level if the alignment of sensors is in the direction of the g force.

#### 4.4 TABULATION OF LIQUID DETECTION SYSTEM DESIGN AND PERFORMANCE FEATURES

As a result of inquiries sent to manufacturers who have developed or are developing cryogenic liquid detection systems, a review of present, state-of-the-art propellant gaging systems was performed. Table 4.4-1 is a summation of manufacturer data sheets specifying accuracy, stability, power requirements and operational gravity requirements.

Table 4.4-1. Liquid Detection Systems Design and Performance Features

MANUFACTURER	ACCURACY	STABILITY	POWER REQUIREMENTS	GRAVITY REQUIREMENTS	REMARKS
Acoustica Associates, Inc.	+0.50 inch	200 hours	10 watts	Positive g	Ultrasonic Sensor System
Acoustica Associates, Inc.	0.1 inch	1000 hours	7 watts/unit LH2 3.5 w/unit LOX	Positive g	Discrete Level Sensor System
Acoustica Associates, Inc.	+1 to +2% Full to Empty	200 hours Between Calibration	35 watts	Positive or Zero g	Infrasonic Sensor System
Bendix Corp.	+10 to +1% Full to Empty	200 hours Between Calibration	30 watts	Positive or Zero g	Radio Frequency Sensor System
Conrac Corp.	+1.5 to 0.5% Full to Empty	200 hours Between Calibration	27 watts	Positive or Zero g	Radiation Sensor System
Industrial Nuclear, Inc.	-2.0%	200 hours Between Calibration	40 watts	Positive or Zero g	Radiation Sensor System
Simmonds Precision Corp.	+0.5%	200 hours	30 watts	Positive g	Coaxial Cylinder Capacitance System
Trans-Sonics Corp.	+2.0%	200 hours Between Calibration	50 watts	Positive or Zero g	Peripheral Capacitance System
TWC, Inc.	+1 to +2% Full to Empty	200 hours	7 watts	Positive or Zero g	Infrasonic Sensor System
Tyco Laboratories	+2.0%	200 hours	7 watts	Positive or Zero g	Radiation Sensor System
United Controls	+0.06 inch	1000 hours	7 watts/unit	Positive g	Discrete Level Sensor System



#### BIBLIOGRAPHY

- [1] F. F. Liu, "Dynamic Phase Transitional Phenomena Associated with Cryogenic Hydrogen Flow in the Temperature Range of From 20°K to 23°K; Some Experimental Observations"
- [2] D. H. Weitzel, J. E. Cruz, L. T. Rowe, R. J. Richards and D. B. Mann, "Instrumentation for Storage and Transfer of Hydrogen Slush," Cryogenics Division Institute for Basic Standards, National Bureau of Standards
- [3] R. C. Binder, "Fluid Mechanics," third edition, pages 203 through 241.
- [4] C. L. Britton, Telecon, Colorado Engineering Experimental Station, January 1972.
- [5] D. Weitzel, Telecons, National Bureau of Standards, Boulder, Colo., November 1971 and January 1972.
- [6] D. A. Ellerbruch, "Microwave Methods for Cryogenic Liquid and Slush Instrumentation," Cryogenic Division, N.B.S. Institute for Basic Standards, Boulder, Colo.
- [7] Rosemount Engineering Co., "Acceptance Test Procedure for Mass Flow Sensors REC Models 124B and 124C NAA/S&ID Part ME449-0015."
- [8] "MC449-0015, Transducer, Mass Flow" Rev. E, dated 23 November 1965.
- [9] Bendix, Instruments and Life Support Division, Bulletin 1619110 dated 15 February 1967\*, and "Summary of Flowmeter Survey Results."  
\*TYPE 9133 Fuel Flow Transmitter Publication 2805-SA-70(401), TYPE 9164 Flow Rate Transmitter Publication 2805-B-70(40).
- [10] W. Treasure, R. Hradek, Facility Contact, Bendix, Davenport, Iowa, September 1971.
- [11] Cox Instruments, Bulletins CA8603, CA-7601, and CC7601.1.
- [12] D. Newlett & W. Kruger, Facility Contact, Cox Inst., Mich., Sept. 1971.
- [13] Exstec Incorporated, Bulletins VS-21970, TD-1, TD-48, TD-5, TD-6, TD-9, and TD-10.
- [14] R. J. Concannon, "EDC Technical Proposal, Business and Management Information for Mass Flowmeters for Space Shuttle," document No. 710527 dated May 5, 1971.
- [15] Fisher and Porter, Catalog C10C dated June 1968.
- [16] Fisher and Porter, Technical Information 10C-4 dated June 1968.
- [17] Flow Technology Incorporated, Bulletins (3).



BIBLIOGRAPHY (continued)

- [18] Foxboro, Bulletins GS1-7B1B, GS/-7A10A, and GS1-7B1A.
- [19] W. J. Alspach, C. E. Miller and T. M. Flynn "Mass Flowmeters in Cryogenic Service," Institute of Materials Research National Bureau of Standards, Boulder, Colorado.
- [20] Foxboro Mass Flow Metering System Model SC11, Installation, Operation and Maintenance Instruction SI 1-00300.
- [21] C. F. Taylor and D. B. Pearson, "A True Mass Cryogenic Flowmeter," I.S.A. Transactions, 5(203-210) 1966.
- [22] J. M. Benson, W. C. Baker, E. Easter, "Thermal Mass Flowmeter," presented at the So. Calif. Meter Assoc., Los Angeles, California, on June 19, 1969.
- [23] H. S. Bean, Fluid Meters, Sixth Edition, Pages 93 and 179, 6, 131.
- [24] J. G. Rusnak, E. R. Wuori, M. R. Minell "Linear Momentum Mass Flowmeter Design and Performance," 2-15-194 dated 15 February 1971.
- [25] E. R. Wuori, and J. J. Rusnar, "Cryogenic Mass Flowmeter," Tech. Report AFRPL-TR-71-83, September 1971.
- [26] J. G. Rusnak, "Linear Momentum Mass Flowmeter 69-529," Honeywell Aerospace Division, Minneapolis, Minnesota.
- [27] O. F. Rice, E. Wuori, J. Jensen, Facility Contact, Honeywell, Inc., Minn., September 1971.
- [28] M. November, Facility Contact, ITT Barton, Cal., June 1971.
- [29] ITT Barton, Process Inst. and Controls, Technical Information No. 13-G1-56, "The Theory and Operation of Vibration Type Densitometers," dated March 4, 1971.
- [30] Dr. F. Liu, Facility Contact, Quantum Dynamics, Cal., June 1971.
- [31] Quantum Dynamics, Bulletins 5.2, 5.5, 5.1, 5.3, and 5.4.
- [32] F. F. Liu, "Measurement of Two-Phase Hydrogen Flow Under Dynamic, Slip and Steady Flow Conditions - Recent Experimental and Theoretical Development."
- [33] Ramapo Instrument Company Bulletin.
- [34] Mead Stapler, "Drag-Body Flowmeter," Ramapo Inst. Co., preprint form Instruments and Control Systems, November 1962.



BIBLIOGRAPHY (continued)

- [35] W. Huemmler, North American Rockwell, Calibration and Facilities Contact, January 1972.
- [36] J. Maybach, Telecon, Rosemount Engineering, January 1972.
- [37] Rosemount Engineering Co., Bulletin 1241 and "R.E.C. Test Procedure 66411C Rev. M."
- [38] Simmonds Precision, "Mass Fuel Flow Systems."
- [39] J. G. Olin, Telecon, Thermo Systems, Inc., November 1971.
- [40] Thermo-Systems, Inc., Bulletin, No. 1750 "Series 352 Mass Flowmeters."
- [41] R. Siev, S. K. Yoder, "Hydrogen Mass Flowmeter Development," Aerojet General Report No. 2048 (Final), Contract No. AF33(616)-6811, Project 3151 Tasks 30459 and 30460, July 1961.
- [42] Development of a Zero-Gravity Propellant Gauging Flight Experiment for MDL-HSQ Program, Acoustica Associates, Inc., Technical Report AFRPL-TR-67-73 (infrasonic).
- [43] Fluid Measurement and Control Systems, Acoustica Associates, Inc., Acoustica Sonometer (ultrasonic and point sensor).
- [44] Propellant Gauging and Control in the Space Age, Acoustica Associates, Inc. (point sensor).
- [45] Summary Report RF Quantity Gauging System, Bendix Corp., Publication No. 4684-70 (radio frequency).
- [46] Final Report on "Performance Studies to Determine the Feasibility of Various Techniques for Measuring Propellant Mass Aboard Orbiting Space Vehicle," Industrial Nucleonics Corp., NASA Contract NAS8-21014 (radiation)
- [47] Simmonds Precision Products Applications for Space Programs, Simmonds Precision Proposal 20202 (capacitance and radio frequency).
- [48] Capacitance Propellant Gauging Study for Orbiting Spacecraft Final Development Report, June, 1967, Trans-Sonics (capacitance).
- [49] Design Optimization of the Radiotracer Propellant Gauge, TRW Technical Report (AFRPL-TR-66-213) (radiation).
- [50] Nucleonic Cryogenic Propellant Gauging System, General Nucleonics Division of Tyco Laboratories, Final Technical Report (AFRPL-TR-69-145) (radiation).